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RESEARCH MEMORANDUM

EFFECT OF LINER AIR-ENTRY HOLES, FUEL STATE, AND COMBUSTOR

SIZE ON PERFORMANCE OF AN ANNULAR TURBOJET COMBUSTOR

AT LOW PRESSURES AND HIGH AIR-FLOW RATES

By Carl T. Norgren and J. Howard Childs

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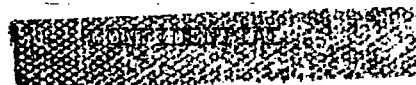
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SUMMARY

As part of a general program to determine design criteria for turbojet combustors, an annular combustor was developed by utilizing the design principles evolved in previous investigations and by making 12 design changes to optimize the altitude performance of the combustor. Although the combustor was developed for liquid fuel injection, heated liquid and vapor fuels gave higher combustion efficiencies at the severe operating conditions. At conditions simulating cruise speed at 80,000 feet in a typical turbojet with a 5.2 pressure ratio engine, the heated liquid and vapor fuels gave combustion efficiencies 18 and 23 percent, respectively, above the efficiency obtained with liquid fuel. With all three fuel types the combustion efficiency was higher at severe operating conditions than the efficiency of any of 14 turbojet combustors previously investigated. At rated engine speed the efficiency was above 97 percent with both liquid and vapor fuels at altitudes up to 65,000 feet. The combustion efficiency was slightly increased by increasing the air-flow rate per unit combustor frontal area to a value 30 percent above that used in current engine design. A further increase in the air-flow rate to a value 69 percent above that of current practice resulted in markedly lower combustion efficiencies at the higher fuel-air ratios.

The combustor operated with high combustion efficiency at conditions where a similar but smaller combustor would not operate in a previous investigation; the better performance of the combustor may therefore be due chiefly to its larger size. Combustion efficiencies obtained in previous investigations with 14 different turbojet combustors at comparable operating conditions show a general trend of increase in efficiency with increase in combustor size.

The total-pressure drop of the combustor was approximately twice as great as the value obtained with some production-model combustors. The combustor-outlet temperature profiles followed the pattern generally



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2709

desired in turbojet engines. No investigation was made of the combustor durability, carbon-forming tendencies, or other low-altitude operating problems.

INTRODUCTION

Trends toward higher flight speeds and higher flight altitudes for military aircraft result in a need for larger (higher thrust) turbojet engines and engines which operate more efficiently at high altitudes. This means that combustor size must be increased and that the combustion efficiency must be increased at the severe, low-pressure conditions encountered with reduced-throttle operation at high altitudes. The attendant improvements in compressor performance may be expected to make possible higher air-flow rates per unit compressor frontal area. If the combustor is not to become the engine component requiring the greatest frontal area, then combustors must be developed which can produce high combustion efficiencies at high air-flow rates per unit combustor frontal area.

Research at the NACA Lewis laboratory on designs for annular turbojet combustors (references 1 to 3) has resulted in improved altitude performance of these combustors. Other NACA research (references 4 and 5) has shown that the use of vapor fuel in lieu of the design (liquid) fuel in a turbojet combustor improved the combustion efficiency at severe operating conditions.

The research reported herein consisted of a direct-connect duct investigation of a one-quarter segment of a $25\frac{1}{2}$ -inch-diameter annular turbojet combustor. This research had a fourfold objective: (1) to develop a combustor using design techniques evolved in previous investigations (references 1 to 3) which will provide high combustion efficiency at low-pressure operating conditions; (2) to investigate the performance of this combustor with heated liquid and vapor fuels using the conventional liquid-fuel injection system; (3) to determine the combustion efficiency of this combustor at the high air-flow rates per unit frontal area which may be produced by future improvements in compressor design; and (4) to compare the efficiency of this combustor with similar data obtained in a previous investigation with a similar, but smaller combustor (unpublished data) in order to show the effect of combustor size on efficiency.

An annular combustor configuration was selected for this investigation because this configuration best utilizes the space available for combustion in a turbojet engine. The fuel injection system was made similar to those used in all annular combustors previously investigated at this laboratory, and consisted of hollow-cone-spray pressure atomizers

located at the upstream end of the combustor liner and injecting fuel in the downstream direction. The selection of combustor size and liner design was based on the results of previous investigations in the manner described in the following paragraphs.

Design modifications made with two different annular turbojet combustors by altering the size and arrangement of the circular air-admission holes in the combustor liner resulted in improved combustion efficiencies and altitude operating limits (reference 1 and unpublished data). With both these combustors the best altitude performance was obtained with approximately the same arrangement of circular holes in the upstream portion of the combustor liner. In reference 2 further design modifications were made in order to improve the combustor-outlet temperature profile. Narrow longitudinal slots for admission of air through the upstream portion of the liner were shown to permit better control of the outlet-temperature profile. The combustion efficiencies obtained in reference 2 were about the same as the efficiencies obtained with the optimum arrangement of circular holes in this same combustor (unpublished data), indicating that the longitudinal slots for air admission did not afford any important gains in combustion efficiency. In reference 3 the air-admission slots were utilized in the design of a larger combustor. This slotted annular combustor of reference 3 is listed as combustor G in reference 6, where its combustion efficiency is compared with that of various other turbojet combustors. These performance comparisons show that the slotted annular combustor of reference 3 produces the highest combustion efficiencies at the severe operating conditions of the 14 turbojet combustors of reference 6.

Since the earlier investigations with a smaller combustor had shown that slots for air admission provide no important increase in combustion efficiency over the values attainable with circular holes, it would appear possible to obtain combustion efficiencies comparable with those of the slotted annular combustor of reference 3 through the use of the optimum arrangement of circular holes in a combustor of the same size. Previous investigations (reference 7) had shown that combustor liners having circular holes are far less subject to warping than the liners having narrow longitudinal slots for primary air admission. Consequently, the combustor selected for the investigation reported herein was made identical in size to the slotted annular combustor of reference 3, and the design included an arrangement of circular holes in the upstream portion of the liner which was similar to the optimum hole arrangement evolved in reference 1. Rectangular slots were used in the downstream portion of the liner because previous experience (unpublished data) had shown these to be a suitable means for obtaining the desired combustor-outlet temperature profile.

With this basic combustor configuration, a total of 12 design modifications was made to optimize the performance; that is, to obtain

the best combination of high efficiency, low pressure drop, and desired outlet-temperature profile. The experimental investigation with the final combustor (model 13) included combustion efficiencies, pressure losses, and outlet-temperature profiles. The investigation was conducted with liquid, heated liquid, and vapor fuels and with several fuel atomizers. Low-pressure operating conditions were investigated to simulate high-altitude flight with air-flow rates per unit combustor frontal area which are typical of current engine design practice, 30 percent above current practice, and 69 percent above current practice. The combustion efficiency data for a range of operating conditions were generalized to fall on a common curve, and this correlation was used to predict the combustion efficiency to be expected with the model 13 combustor at various flight conditions in a turbojet engine. Comparisons were made of the performance of the model 13 combustor with similar data obtained in previous investigations with other combustors to show the relative performance of the model 13 combustor and to indicate the effect of combustor size on performance.

APPARATUS

Installation

A diagram of the combustor installation is shown in figure 1. The combustor-inlet and combustor-outlet ducts were connected to the laboratory-air supply and low-pressure exhaust systems, respectively. Air-flow rates and combustor pressures were regulated by remote-controlled valves upstream and downstream of the combustor. The combustor-inlet air temperature was controlled by an electric air heater. Fuel preheat was supplied by an electric resistance-type heater.

Instrumentation

Air flow was metered by a concentric-hole, sharp-edge orifice installed according to A.S.M.E. specifications. Liquid fuel flow was metered by a calibrated rotameter; vapor fuel flow, by a calibrated sharp-edge orifice. Thermocouples and pressure tubes were located at the combustor inlet and outlet planes as indicated in figure 1. The number, type, and location of these instruments at each plane is indicated in figure 2. The combustor-outlet thermocouples were located at centers of equal areas in the duct. Details of construction of the thermocouples and pressure tubes are shown in figure 3 and are the same as those presented in reference 3. Pressure tubes were connected to absolute manometers; thermocouples were connected to a recording potentiometer.

Combustors

A total of 13 combustor configurations was investigated. Each combustor consisted of a one-quarter segment (90°) of a single-annulus combustor having an outside diameter of $25\frac{1}{2}$ inches, an inside diameter of $10\frac{5}{8}$ inches, and a length from fuel atomizers to combustor-outlet thermocouples of approximately 23 inches. The maximum combustor cross-sectional area was 105 square inches (corresponding to 420 square inches for the complete combustor). Ten simplex hollow-cone-spray pressure atomizers (corresponding to 40 atomizers in the complete combustor) injected the fuel in the downstream direction from the upstream end of the combustor liner. Several sets of atomizers of different capacity were used in the course of the experimental investigation.

Figure 4 shows a three-quarter cut-away view of the final combustor (model 13) and figure 5, a longitudinal cross section of the combustor. The arrangement of air-admission holes in the liner of model 13 combustor is shown in figure 6. In the present discussion the upstream one-half of the liner will be referred to as the primary zone and the second one-half, as the secondary zone.

Fuels

The liquid fuel used in this investigation was MIL-F-5624A grade JP-4. The inspection data for this fuel are presented in table I. The vapor fuel was commercial propane.

PROCEDURE

Combustion efficiency and combustor total-pressure loss data were recorded for a range of fuel-air ratio at the following conditions:

Condition	Combustor-inlet total pressure (in. Hg absolute)	Combustor-inlet total temperature ($^\circ\text{F}$)	Air-flow rate per unit combustor area ^a (lb/(sec)(sq ft))	Simulated flight altitude in reference engine at cruise rpm (ft)
A	15	268	2.14	56,000
B	8	268	1.14	70,000
C	5	268	0.714	80,000
D	15	268	2.78	56,000
E	15	268	3.62	56,000

^aBased on maximum combustor cross-sectional area.

These conditions simulate operation of the combustor in a reference turbojet engine, which is a typical 5.2 pressure ratio turbojet, operating at a Mach number of 0.6. The cruise speed of the engine is assumed to be 85 percent of the rated rotor speed. Test conditions A through C require air-flow rates per unit combustor frontal area which are typical of current turbojet engines. Test conditions D and E require air-flow rates which are 30 percent and 69 percent, respectively, above current practice.

In the preliminary research necessary to evolve the final combustor design, limited data were recorded with JP-4 fuel and 10.5-gallon-per-hour atomizers in each combustor at one or more of test conditions A, B, and C. With the final (model 13) combustor, more extensive data were recorded, as indicated in the following table:

Fuel	Fuel atomizer capacity (gal/hr) ^a	Fuel spray angle (deg) ^a	Conditions
JP-4	10.5	60	A,B,C,D,E
	3.0	60	A,B,C
Heated JP-4 ^b	10.5	60	A,B,C
Propane	10.5	60	B,C
	30	70	A,B,C,D,E
	60	70	E

^aRated at 100 lb/sq in. pressure differential; liquid fuel.

^bFuel temperature, 300° F.

Combustion efficiency was computed as the percentage ratio of actual to theoretical increase in enthalpy from the combustor-inlet to the combustor-outlet instrumentation planes using the method of reference 8. For calculation of combustor-outlet enthalpy, the temperature was computed as the arithmetic mean of the 30 outlet thermocouple indications; no corrections were made for radiation or velocity effects on the thermocouple indications.

Combustor reference velocities were computed from the air mass-flow rate, the combustor-inlet density, and the maximum combustor cross-sectional area (105 sq in.). The total-pressure loss was computed as the dimensionless ratio of the total-pressure loss to the combustor reference dynamic pressure using the method of reference 3. The radial

2709
distribution of temperatures at the combustor outlet was determined at each test condition investigated and at two values of combustor temperature rise (approximately 680° and 1180° F, the required values at 85 and 100 percent rated speed in the reference turbojet engine at altitudes above the tropopause). The temperature at each of the 5 radial positions was computed as the average of four thermocouple readings at each radial position (see fig. 2(b)). The temperature rake at each side wall of the combustor was not included in these average temperatures in order to minimize the effects of the side walls on temperature readings. The optimum combustor-outlet radial temperature profile was considered to be that shown in figure 7; this temperature profile represents an approximate average of those profiles required or desired in various turbojet engines.

RESULTS

The results obtained in the investigation of the preliminary combustor configurations are discussed briefly in appendix A. The following results were obtained with the final (model 13) combustor. The model 13 combustor was considered to be a near-optimum design for the particular combustor size and shape, fuel, and fuel injection system which were selected and for the particular test conditions investigated; it gave the best over-all performance of the 13 combustor configurations investigated. The experimental data for the model 13 combustor are presented in table II. A tabulated list of all symbols is presented in appendix B.

Combustion Efficiencies

The combustion efficiencies obtained with liquid, heated liquid, and vapor fuels are presented in figures 8, 9, and 10, respectively, for a range of fuel-air ratio at each of three inlet pressures (test conditions A, B, and C). The data of figures 8 and 9 were obtained with 10.5-gallon-per-hour, 60° fuel atomizers. These same atomizers were used with vapor fuel to obtain a part of the data of figure 10. Additional data are shown in figure 10 for 30-gallon-per-hour, 70° atomizers.

Duplicate data were recorded at a few values of fuel-air ratio at test conditions B and C, and these check data are indicated by tailed symbols in figure 8. The check data showed an average deviation of ± 2 percent.

Figure 11 presents combustion efficiencies at the same test conditions as the preceding figures (test conditions A, B, and C) with liquid fuel and improved fuel atomization through the use of 3.0-gallon-per-hour, 60° atomizers.

Figures 12 and 13 show combustion efficiencies obtained at three air-flow rates (test conditions A, D, and E) with liquid and vapor fuels, respectively. The data of figure 12 were obtained with 10.5-gallon-per-hour, 60° fuel atomizers. The data of figure 13 for vapor fuel were obtained with two atomizer capacities, 30-gallon-per-hour and 60-gallon-per-hour atomizers. The 60-gallon-per-hour atomizers were required to obtain the higher fuel-air ratios at test condition E without causing the pressure drop in the fuel injectors to exceed the propane fuel supply pressure, which was approximately 80 pounds per square inch gage.

Pressure Losses

The pressure losses through the combustor are presented in figure 14. The dimensionless ratio of the total-pressure drop to the reference dynamic pressure $\Delta P/q_r$ is plotted as a function of the combustor-inlet to combustor-outlet density ratio ρ_1/ρ_2 . The expected straight-line relation is obtained, but some separation occurs between data recorded at different pressures.

Outlet Temperature Profiles

Figures 15(a) and 15(b) show combustor-outlet radial temperature profiles with liquid and vapor fuels, respectively, at each condition investigated and at two values of combustor temperature rise (approximately 680° and 1180° F). The desired temperature profile from figure 7 is included for comparison.

DISCUSSION

Fuel State

A comparison of the curves from figures 8 to 10 is presented in figure 16 to show the effect of fuel state on combustion efficiency. Only slight differences exist among the liquid, heated liquid, and vapor fuels at the two higher pressures (conditions A and B). At the most severe test condition investigated, corresponding to cruise speed at 80,000 feet altitude (condition C), the combustion efficiency with the vapor fuel was 23 percent above that with liquid fuel and the efficiency with heated liquid fuel was 18 percent above that with liquid fuel; these comparisons are made at the fuel-air ratios required with each fuel to give the 680° F combustor temperature rise required for cruise speed in the reference engine at 80,000 feet altitude. These values of fuel-air ratio are indicated by circular symbols on each of the curves for test condition C in figure 16.

The curves for liquid and vapor fuel at the highest air-flow rate (condition E, figs. 12 and 13) show that vapor fuel also provides a significant increase in combustion efficiency at this severe operating condition. The higher combustion efficiency of the vapor fuel at severe operating conditions is in accord with the results of previous investigations of liquid and vapor fuels in turbojet combustors (references 4 and 5).

A comparison of the data of figure 11 with the data of figure 8 shows that the smaller capacity atomizers gave no significant increase in efficiency at any of the conditions investigated, and that they caused a slight decrease in efficiency at the lowest pressure (condition C). Thus the higher combustion efficiencies obtained with heated liquid and vapor fuels were not obtained by finer mechanical atomization of the liquid fuel.

Performance Comparisons

Most turbojet combustor investigations have been conducted at test conditions simulating operation of each combustor in its particular engine; consequently, it is difficult to find data obtained with different combustors at identical operating conditions. The combustion parameter $V_r/p_1 T_1$ (where V_r is the combustor reference velocity in ft/sec, calculated from inlet density, mass-flow rate, and maximum combustor cross-sectional area; p_1 is the combustor-inlet static pressure in lb/sq ft absolute; and T_1 is the combustor-inlet temperature in $^{\circ}\text{R}$) can be used, however, to reduce the combustion efficiencies obtained at any test conditions to a single curve for each combustor and each fuel, as shown in reference 6. A comparison of these curves therefore affords a comparison of the performance of various combustors even though the experimental conditions investigated might be different for the various combustors.

In figure 17 are plotted the combustion efficiency data of figures 8, 9, 10, 12, and 13 as a function of the combustion parameter $V_r/p_1 T_1$. This form of the parameter is used herein rather than its reciprocal $p_1 T_1/V_r$ as derived in reference 6 because the resulting correlation curves do not have the extreme curvature noted in reference 6. The efficiency data of figure 17(a) are for a combustor temperature rise of 680°F , which is the value required in the reference engine at cruise speed and altitudes above the tropopause. Figures 17(b) and 17(c) present similar data for values of temperature rise of 402° and 1180°F , which are the required values of temperature rise for 75- and 100-percent rated speed at altitudes above the tropopause. These values of required temperature rise were obtained from

engine performance curves which were extrapolated to the higher altitude conditions by assuming constant efficiencies of engine components other than the combustor. Figure 18 presents a comparison of the curves of figure 17 for the model 13 combustor with liquid, heated liquid, and vapor fuels with similar curves for two of the better combustors (combustors G and L) reported in reference 6. Combustor G from reference 6 is the slotted annular combustor of reference 3, which produced the highest combustion efficiencies of the 14 turbojet combustors reported in reference 6. Combustor L from reference 6 is one of the better production-model combustors. Figure 18 shows that with any of the three fuel types investigated, the model 13 combustor produced a higher combustion efficiency at severe operating conditions than any of the 14 combustors of reference 6.

Estimated Flight Performance

Figure 19(a) shows the estimated combustion efficiency of the model 13 combustor with liquid fuel at various flight conditions in the reference turbojet engine. The curves of constant combustion efficiency were obtained as follows: At each flight condition indicated on figure 19(a) by a circular symbol, the required temperature rise and the value of the combustion parameter $V_r/p_i T_i$ were obtained from the engine performance curves. For each value of the combustion parameter thus obtained the corresponding efficiency was then obtained from figure 17 for values of temperature rise above and below the required value. The efficiency at the required temperature rise was then obtained by interpolation. These values of combustion efficiency were next indicated in figure 19(a) beside the appropriate circular symbols. Finally, the constant efficiency curves were drawn to fit the pattern indicated by these circular symbols.

The three rectangular data points in figure 19(a) at 85 percent rated speed represent actual experimental data where the test conditions accurately simulated flight operation at the conditions indicated on the figure. The combustion efficiencies listed beside each of these three data points match well with the values expected from interpolation between the curves, indicating the validity of figure 19(a). The curves of figure 19(a) show that with liquid fuel the model 13 combustor operated at efficiencies above 97 percent up to an altitude of 65,000 feet at rated engine speed.

Similar data are presented in figure 19(b) for the model 13 combustor operating with vapor fuel. Again the circular symbols represent data calculated by use of figure 17, and the square symbols represent experimental data. With vapor fuel the model 13 combustor operated at efficiencies above 97 percent up to an altitude of 65,000 feet at rated engine speed.

With both liquid and vapor fuel the model 13 combustor supplied sufficient temperature rise to operate the turbojet engine at 85 percent rated speed and an altitude of 80,000 feet. Thus the altitude operating limits of the engine would lie above 80,000 feet at 85 percent rated speed.

High Air-Flow Rates

The combustion efficiency of the model 13 combustor was slightly increased with both liquid and vapor fuels when the air-flow rate per unit frontal area was increased to a value about 30 percent above current design practice (figs. 12 and 13). This result is contrary to the usual trend of decreased efficiency with increased velocity which has been generally noted in previous investigations. When this air flow was further increased to a value about 69 percent above current practice, the efficiency with both fuels was markedly decreased at high fuel-air ratios. The vapor fuel gave higher efficiencies than the liquid fuel at the highest air-flow rate, indicating that a combustor designed to make better use of the vapor fuel might constitute one means for obtaining high efficiencies at higher air-flow rates.

Combustor Size

A development program similar to that reported herein was previously conducted with an annular combustor of smaller size (unpublished data). The model 13 combustor evolved herein and the smaller combustor previously investigated are similar in many respects: (1) both combustors are annular combustors with similar fuel injection systems; (2) both combustors have approximately the same arrangement of circular holes in the upstream end of the combustor liner; and (3) both combustors produced higher efficiencies than the various other combustor configurations which were investigated in their respective development programs. These combustors differ primarily in size. A comparison of the performance of these two combustors should therefore provide some indication of the effect of combustor size on performance.

A significant comparison of the combustion efficiency of these two combustors is not available because the combustion efficiencies of the smaller combustor were measured only at favorable conditions corresponding to low values of the combustion parameter $V_r/p_1 T_1$ where most combustors give efficiencies near 100 percent. The best available performance comparison between these two combustors is therefore shown in figure 20. The altitude operating limits of the smaller combustor appear as a straight line. The experimental data obtained with the model 13 combustor are also included in figure 20 to show that the model 13 combustor operated with high efficiency over a wide range of conditions where the smaller combustor would not operate.

The indicated effect of combustor size may possibly be the result of liquid fuel "wash" on the walls of the combustor liner. Reference 9 shows air- and fuel-flow patterns in a turbojet combustor with no burning occurring, and an appreciable quantity of the liquid fuel impinges on the walls of the liner and flows along the walls as a continuous liquid film. Liquid fuel "wash" along the walls of the liner has also been observed under burning conditions in some combustors. Large quantities of liquid fuel on the walls would be expected to result in a decrease in combustion efficiency. Since the fuel atomizers used in the smaller combustor had the same flow capacity and spray angle as those used in the model 13 combustor, it would be expected that they would cause much greater quantities of liquid fuel to impinge on the walls of the smaller combustor.

Further indication of a possible important effect of combustor size on combustion efficiency is shown in figure 21. Values of combustion efficiency obtained in previous investigations with 14 different turbojet combustors at operating conditions of equal severity

($V_r/P_1 T_1 = 100 \times 10^{-6}$) are plotted in figure 21 as a function of a combustor hydraulic radius. The efficiency data for these fourteen combustors were taken from the curves of reference 6. The combustor hydraulic radius is defined as the ratio of the cross-sectional area inside the combustor liner to the wetted perimeter of the combustion zone at the point where the undisturbed fuel spray would touch the liner walls. This hydraulic radius is also the volume-to-surface ratio per unit length of the combustion zone at the point where the fuel is dispersed across the combustion zone. A combustor hydraulic radius was selected as an index of the effect of combustor size on efficiency because the surface-to-volume ratio of small-scale combustion apparatus is known to have an important effect on flammability limits, as shown in reference 10. The point where the undisturbed fuel spray would touch the liner walls was arbitrarily selected as the plane at which the hydraulic radius would be evaluated; a better correlation of the data of figure 21 might possibly be obtained by using values of hydraulic radius which are evaluated differently.

Figure 21 shows that the data points for most of the 14 combustors of reference 6 fall within ± 10 percent of a single curve, and this curve shows an increase in combustion efficiency with increase in combustor size throughout the range of size investigated. The data point for the model 13 combustor falls near the upper end of the curve in figure 21. Other design factors besides that of size are, of course, important, and this accounts for some of the scatter of data points in figure 21. For example, combustors C and D are identical except for changes in the primary air holes in the liner, and combustors I and J are identical except for changes in the fuel atomizer.

Pressure Losses, Outlet Temperature Profiles, and Other
Performance Characteristics

For isothermal (no combustion) flow, the average value of $\Delta P/q_r$ in figure 14 is about 25; this value is approximately twice as great as the corresponding value for some production-model combustors. The design changes which were made in an attempt to reduce this pressure drop were unsuccessful, as noted in appendix A; with a more extensive effort it might, however, be possible to significantly reduce this pressure drop.

The combustor-outlet temperature profiles in figure 15 are similar to the profile generally desired in turbojet engines, with low temperatures near the blade hub and blade tip positions and a maximum temperature at about 85 percent of the blade height. The maximum circumferential scatter of individual thermocouple indications was $\pm 200^\circ \text{F}$ at any radial position. The outlet-temperature profiles for the model 13 combustor were not so good as those of some of the preliminary combustors investigated (for example, see appendix A) because the model 13 combustor was evolved as the result of design compromises to obtain the best over-all combination of high efficiency, low pressure drop, and a desired pattern of outlet temperatures.

The low altitude performance of the combustor was not investigated; consequently, little is known regarding its durability or carbon-deposition characteristics. No carbon deposits or warping of the liner were observed during this investigation, but the test conditions were not in the range where these problems are severe.

SUMMARY OF RESULTS

An annular turbojet combustor was developed to give improved performance at high altitudes by utilizing the design principles evolved in previous investigations to obtain the basic combustor configuration and then making 12 minor design changes to optimize the performance of this combustor. The results obtained from the experimental investigation of the model 13 combustor at low pressures and high air-flow rates are summarized in the following paragraphs. The values quoted for simulated flight performance refer to the model 13 combustor in a typical 5.2 pressure ratio turbojet engine at a flight Mach number of 0.6.

1. Although the combustor was developed for liquid fuel injection, heated liquid and vapor fuels injected through the conventional liquid-fuel injection system gave higher combustion efficiencies at the more severe operating conditions. At conditions simulating cruise speed at

80,000 feet altitude, the efficiencies with heated liquid and vapor fuels were 18 and 23 percent, respectively, above the efficiency with liquid fuel. At cruise speed at 70,000 feet, the differences in efficiency between the fuels were slight.

2. With all three fuel types investigated (liquid, heated liquid, and vapor) the combustion efficiency at severe operating conditions was higher than the efficiency of any of 14 turbojet combustors previously investigated. At rated engine speed the combustion efficiency was above 97 percent with both liquid fuel and vapor fuel at altitudes up to 65,000 feet.

3. At cruise speed at 56,000 feet altitude, the combustion efficiency was slightly increased by increasing the air-flow rate per unit combustor frontal area to a value 30 percent above that used in current engine design practice. At an air-flow rate 69 percent above current practice, however, the efficiency was markedly decreased at high fuel-air ratios.

4. A smaller, similar annular combustor which was previously developed to obtain high performance would not operate at many conditions at which the model 13 combustor produced high efficiency. The better performance of the model 13 combustor may therefore be due chiefly to its size. A comparison of the combustion efficiency previously obtained with 14 turbojet combustors at comparable operating conditions shows that for most of the combustors the efficiency increases with increase in combustor size.

5. The total-pressure drop through the combustor was approximately twice as great as the pressure drop of some production-model combustors.

6. The combustor-outlet temperatures followed the radial pattern generally desired in turbojet engines; that is, the temperatures were low at the extreme blade hub and blade tip positions and were a maximum at about 85 percent of the blade height. The maximum circumferential variation of individual thermocouple indications from the mean temperature at any radial position was about $\pm 200^{\circ}$ F.

7. The low-altitude performance of the combustor has not been investigated; consequently, little is known regarding its durability or carbon-deposition characteristics.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio Sept.

APPENDIX A

EVOLUTION OF MODEL 13 COMBUSTOR

2709 The design modifications consisted of two distinct types: (1) secondary zone modifications, which primarily affected the outlet-temperature profile and the combustor pressure drop; and (2) primary zone modifications, which primarily affected the combustion efficiency. The greatest deficiency of the model 1 combustor was its outlet-temperature profile; hence secondary zone modifications were made first.

Secondary Zone Modifications

Figure 22 shows the combustor liner design for three combustors (models 1, 2, and 3), and figure 23 shows the radial outlet-temperature profiles of these combustors. Combustor models 1 to 3 had approximately the same total open area in the liner and hence the same pressure drop. Model 1 produced temperatures which were too low near the inner wall (turbine blade hub) and too high near the center of the duct (fig. 23(a)).

Model 2 was evolved to improve the temperature profile of model 1. This combustor had less open area on the inner wall of the liner and correspondingly greater open area on the outer wall, resulting in increased temperatures near the blade hub (fig. 23(b)). In addition, the model 2 combustor had a greater spacing between the air-admission slots in the inner wall of the liner, permitting the cold air entering through these slots to penetrate as individual jets into the hot gases to produce alternate hot and cold "corridors" in the combustor. With the smaller slot spacing of the preceding combustor (model 1), these air jets did not penetrate as individual jets, but displaced the hot gases toward the center of the duct and coalesced to form a cold layer of gas near the turbine blade hub. These deductions are based on observations of the flame patterns in the combustor and the temperature patterns visible on the side walls of the combustor housing. The improved jet penetration (obtained with the model 2 combustor) served to reduce the temperature in the center of the duct (fig. 23(b)).

The model 3 combustor represented a still further step in the same direction; that is, less open area in the inner wall, correspondingly greater open area in the outer wall, and wider spacing between the slots in the inner wall. A further improvement in outlet-temperature profile resulted (fig. 23(c)).

An increase in the area of the secondary zone liner perforations was required to decrease the pressure drop of the model 3 combustor. The width of the secondary zone slots could not be increased without

reducing the space between the secondary air jets; this would be expected to impair the penetration of these jets as indicated by the experience with combustor models 1 to 3. The slots could not be extended upstream without reducing the length available for combustion. The requisite increase in area of the slots was therefore obtained by changing from 10 slots (fig. 22) to 5 slots (fig. 6); this permitted a 30 percent increase in the area of the secondary air slots in model 13 over that of models 1 to 3. The outlet-temperature profile was slightly impaired by this area increase, but the accompanying decrease (approximately 25 percent) in pressure drop made the over-all performance of the model 13 combustor more desirable.

After the change was made from the 10-slot to the 5-slot secondary zone configuration, three modifications were required to obtain the desired outlet-temperature profile by means of a correct balance between secondary slot area in the outer wall and in the inner wall of the liner (models 11 to 13).

Attempts to greatly increase the area of the secondary air slots (models 5 and 6) resulted in circumferentially uneven temperature profiles and severe local high-temperature regions. Models 5 and 6 also showed no marked lowering of the pressure drop, probably because a large part of the pressure loss was then occurring in the annular flow passages which supply air to the downstream part of the combustor liner.

Additional secondary zone modifications were made in models 7 and 8 to add cooling louvers at the positions indicated in figure 6.

Primary Zone Modifications

Combustor model 4 was similar to model 3 but had 3 rows of holes consisting of ten $3/16$ -inch holes per row located in the inner and outer walls of the liner (for a total of sixty $3/16$ -inch holes in the one-quarter sector) approximately $7\frac{1}{2}$ inches from the upstream end of the liner. These small holes had no measurable effect on performance and were later replaced by a row of cooling louvers.

Combustor models 9 and 10 varied the amount of air admitted behind the fuel atomizer radiation shield (fig. 5). This air flows around the fuel atomizers and emerges into the combustion zone through the holes provided in the radiation shield for each fuel atomizer. Model 9 had a row of $1/16$ -inch holes in the upstream end of the liner walls for admission of this air behind the fuel atomizers; the final model 13 combustor had $1/8$ -inch diameter holes for this purpose, and the model 10 combustor had alternate $1/8$ -inch and $5/32$ -inch holes for this purpose. Thus models 9 and 10 provided less and more air, respectively, around the

fuel atomizers than did model 13. The combustion efficiencies of models 9 and 10 were below that of model 13, indicating that the air admitted around the fuel nozzles has a marked effect on efficiency and further indicating that model 13 provided approximately the optimum quantity of air in this location.

APPENDIX B

SYMBOLS

The following symbols are used in this report:

A_r	reference combustor cross-sectional area, sq ft
f	fuel-air ratio, lb/lb
P_1	combustor-inlet total pressure, in. Hg absolute
ΔP	total-pressure drop through combustor, in. Hg
ΔP_f	fuel manifold pressure (above combustor-inlet pressure), in. Hg
p_1	combustor-inlet static pressure, lb/sq ft absolute
q_r	reference dynamic pressure, in. Hg
T_1	combustor-inlet total temperature, °R
T_o	mean combustor-outlet temperature, °R
ΔT	mean temperature rise through combustor, °F
V_r	combustor reference velocity, ft/sec
W_a	air-flow rate, lb/sec
W_f	fuel-flow rate, lb/hr
η_b	combustion efficiency, percent
ρ_1	combustor-inlet air density, lb/cu ft
ρ_2	combustor-outlet air density, lb/cu ft

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TABLE I - FUEL ANALYSIS



Fuel properties	MIL-F-5624A (JP-4) (NACA fuel 52-53)
A.S.T.M. distillation	
D86-46, °F	
Initial boiling point	136
Percentage evaporated	
5	183
10	200
20	225
30	244
40	263
50	278
60	301
70	321
80	347
90	400
Final boiling point	498
Residue, percent	1.2
Loss, percent	0.7
Aromatics	
A.S.T.M. D-875-46T,	8.5
percent by volume	
Silica gel, percent	10.7
by volume	
Specific gravity	0.757
Viscosity, centistokes	0.762
at 100° F	
Reid vapor pressure,	2.9
lb/sq in.	
Hydrogen-carbon ratio	0.170
Net heat of combustion	18,700

TABLE II - DATA OBTAINED FOR MODEL 13 COMBUSTOR

Run	Combustor-inlet total pressure P_1 (in. Hg)	Combustor-inlet total temperature T_1 ($^{\circ}$ R)	Air flow rate \dot{W}_a (lb/sec)	Air flow rate per unit area \dot{W}_a/A_p (lb/(sec)(sq ft))	Combustor reference velocity V_c (ft/sec)	Fuel flow rate \dot{W}_f (lb/hr)	Fuel manifold pressure (above combustor-inlet pressure) ΔP_f (lb/sq in.)	Fuel-air ratio f	Mean combustor-outlet temperature T_0 ($^{\circ}$ R)	Mean combustor-outlet temperature through combustor ΔT ($^{\circ}$ R)	Combustion efficiency η_b (percent)	Total pressure drop through combustor ΔP (in. Hg)	Combustion parameter $V_c/P_1 T_1$ (ft, lb, sec, $^{\circ}$ R units)
10.5 gal/hr, 60 $^{\circ}$ fuel atomizer; fuel, JP-4													
1	15.0	728	1.580	2.137	80.46	—	—	—	—	—	—	0.914	100.7x10 $^{-6}$
2	—	730	1.557	2.133	80.51	39.5	4.0	0.007047	1248	518	89.92	1.307	100.5
3	—	731	1.558	2.134	80.71	46.4	4.3	0.008272	1322	591	87.87	1.358	100.6
4	—	730	1.558	2.134	80.56	53.9	4.5	0.008610	1403	673	85.72	1.387	100.6
5	—	720	1.582	2.140	79.85	85.0	4.7	0.01156	1522	802	85.90	1.424	100.9
6	—	730	1.553	2.127	80.31	73.6	5.0	0.01316	1651	921	86.98	1.478	100.2
7	—	734	1.554	2.129	80.77	85.9	5.1	0.01535	1773	1039	86.97	1.532	100.3
8	—	735	1.557	2.147	81.68	101.7	5.5	0.01805	1927	1181	86.17	1.618	101.2
9	8.0	728	1.518	1.140	80.51	20.8	2.8	0.006845	1187	469	92.62	0.7180	128.9
10	7.95	722	1.520	1.150	79.70	25.8	2.8	0.006887	1248	527	92.82	0.7408	188.8
11	8.0	728	1.519	1.140	80.31	29.3	3.0	0.007653	1251	525	96.01	0.7753	188.9
12	—	725	1.511	1.138	79.80	40.3	3.3	0.01347	1498	773	80.48	0.7954	188.6
13	—	725	1.5272	1.135	79.78	88.0	3.8	0.01847	1753	1026	80.28	0.8404	187.7
14	—	725	1.522	1.136	79.85	83.5	4.0	0.02187	2025	1300	69.78	0.8677	186.2
15	5.0	729	1.5192	1.112	80.31	21.2	3.3	0.01134	1244	518	92.50	0.8002	301.7
16	—	729	1.5187	1.105	80.48	26.0	4.1	0.01500	1347	518	87.60	0.8293	301.4
17	—	732	1.5187	1.105	80.77	32.0	4.3	0.01714	1393	563	84.58	0.8337	301.4
18	—	722	1.5187	1.105	79.70	37.5	4.3	0.02009	1452	780	81.77	0.8282	301.4
19	—	728	1.5187	1.105	80.48	46.2	4.3	0.02421	1528	799	47.80	0.8307	301.4
20	—	730	1.5187	1.105	79.70	80.0	4.3	0.03214	1833	911	42.11	0.8302	301.4
21	8.0	720	1.527	1.141	80.82	25.8	—	0.008606	1282	552	87.77	0.7400	189.1
22	—	726	1.507	1.138	80.26	41.4	—	0.01384	1555	839	85.47	0.8179	188.6
23	—	730	1.541	1.143	80.97	21.0	—	0.008933	1174	444	85.86	0.7871	188.4
24	—	728	1.522	1.136	80.26	31.0	—	0.01038	1382	654	87.00	0.8012	188.2
25	5.0	729	1.5173	1.108	80.26	21.2	5.3	0.01159	1262	523	84.47	0.8118	300.6
26	—	732	1.5281	1.1234	82.24	25.6	5.8	0.01241	1275	543	80.50	0.8262	306.8
27	—	722	1.5222	1.133	80.21	21.5	5.3	0.01144	1251	509	81.20	0.8076	303.4
28	—	728	1.5205	1.127	80.71	27.0	4.0	0.01442	1331	603	86.32	0.8392	302.3
29	—	734	1.5227	1.180	81.78	32.4	4.3	0.01722	1408	674	55.31	0.8548	303.7
30	—	725	1.5222	1.153	81.02	35.8	4.3	0.01953	1404	676	48.82	0.8538	303.4
10.5 gal/hr, 60 $^{\circ}$ fuel atomizer; fuel, heated JP-4													
31	15.0	720	1.553	2.150	79.29	36.6	19.0	0.006838	1187	447	82.31	1.252	100.4x10 $^{-6}$
32	15.05	732	1.554	2.129	80.31	46.2	20.1	0.008618	1428	586	84.81	1.335	99.70
33	15.0	725	1.553	2.127	79.75	53.7	22.1	0.008605	1587	682	85.04	1.351	100.2
34	—	735	1.553	2.127	80.61	63.9	22.8	0.01143	1498	765	83.45	1.378	100.2
35	—	735	1.556	2.132	80.87	74.4	23.9	0.01328	1628	895	85.29	1.438	100.5
36	—	730	1.537	2.133	80.51	87.2	24.7	0.01556	1784	1034	85.19	1.489	100.5
37	—	735	1.5166	2.145	81.37	103.8	26.5	0.01843	1980	1227	87.21	1.551	101.1
38	8.0	728	1.5347	1.145	80.77	21.7	11.9	0.006889	1180	422	82.84	0.7385	189.4
39	—	725	1.5337	1.142	80.41	25.8	15.7	0.006897	1278	553	87.94	0.7900	189.2
40	—	731	1.5298	1.137	80.68	31.6	14.3	0.01058	1394	653	85.39	0.8088	188.4
41	—	729	1.5354	1.144	81.07	36.9	16.0	0.01227	1494	765	87.23	0.8282	189.5
42	—	734	1.5335	1.142	81.42	43.3	19.1	0.01443	1622	886	87.25	0.8710	189.2
43	—	736	1.5335	1.142	81.65	80.3	20.8	0.01676	1726	990	84.81	0.8676	188.2
44	—	730	1.5305	1.138	80.71	56.0	26.4	0.01940	1828	1096	82.06	0.8907	188.6
45	—	722	1.5286	1.132	79.40	75.8	26.9	0.02547	1974	1282	75.11	0.9082	187.6
46	5.0	730	1.5187	1.105	80.56	20.0	13.5	0.01071	1271	541	89.48	0.8132	301.4
47	—	722	1.5187	1.105	79.70	27.0	17.5	0.01446	1489	767	74.56	0.8700	301.4
48	—	735	1.5187	1.105	83.12	38.6	20.5	0.01794	1558	821	85.28	0.8741	301.4
49	—	725	1.5183	1.100	79.75	38.6	22.3	0.02069	1681	938	65.44	0.8786	301.2
50	—	728	1.5183	1.100	80.26	43.0	—	0.02412	1707	979	59.31	0.8838	301.2
10.5 gal/hr, 60 $^{\circ}$ fuel atomizer; fuel, propane													
51	8.0	725	0.8342	1.143	80.21	25.26	—	0.008412	1310	587	90.02	0.7864	188.4x10 $^{-6}$
52	—	714	0.8312	1.139	78.94	26.96	—	0.008679	1374	680	88.58	0.7922	188.7
53	—	720	0.8302	1.137	79.45	31.03	—	0.01038	1426	706	88.87	0.8095	188.4
54	—	724	0.8342	1.143	80.31	33.40	—	0.01112	1477	753	88.93	0.8330	188.4
55	—	725	0.8322	1.140	80.56	36.28	—	0.01209	1536	810	88.61	0.8729	188.9
56	5.0	722	0.8380	1.1370	82.88	19.65	—	0.01025	1345	623	79.02	0.8880	312.6
57	—	718	0.8142	1.1044	78.53	22.67	—	0.01225	1442	724	77.69	0.8789	298.8
58	—	722	0.8221	1.1182	80.31	25.87	—	0.01275	1507	785	81.40	0.8951	303.4
59	—	725	0.8221	1.1182	80.48	27.84	—	0.01470	1574	851	77.33	0.9149	303.4
60	—	725	0.8221	1.1182	80.51	29.56	—	0.01571	1654	933	79.75	0.9246	304.0
61	—	725	0.8221	1.1182	80.48	32.83	—	0.01750	1714	991	77.72	0.9388	303.4
62	—	735	0.8251	1.193	82.24	35.64	—	0.01886	1777	1042	75.65	0.9739	306.2
63	—	727	0.8226	1.189	80.97	38.29	—	0.02058	1876	1149	77.99	0.9588	303.7
30.0 gal/hr, 70 $^{\circ}$ fuel atomizer; fuel, propane													
64	15.0	724	1.558	2.134	79.80	45.17	—	0.008053	1326	602	98.38	1.507	100.6x10 $^{-6}$
65	—	728	1.580	2.137	80.56	51.63	—	0.008195	1420	692	98.02	1.584	100.7
66	—	734	1.559	2.136	81.02	57.97	—	0.01033	1498	784	97.09	1.608	100.7
67	—	722	1.560	2.137	79.70	65.48	—	0.01186	1587	865	98.21	1.628	100.7
68	—	732	1.580	2.137	80.82	72.03	—	0.01283	1669	937	97.56	1.659	100.7
69	—	725	1.580	2.137	79.80	83.47	—	0.01486	1803	1080	98.34	1.665	100.7
70	—	722	1.560	2.137	79.70	95.05	—	0.01692	1916	1194	95.95	1.685	100.7
71	8.0	726	1.549	1.144	80.58	23.51	—	0.007821	1246	520	85.36	0.8586	189.5
72	—	732	1.510	1.138	80.82	27.84	—	0.009258	1347	615	84.39	0.8924	188.6
73	—	731	1.559	1.145	81.22	32.26	—	0.01072	1441	710	86.80	0.9259	189.7

TABLE II - DATA OBTAINED FOR MODEL 13 COMBUSTOR - Concluded

Run	Combustor-inlet total pressure P_1 (in. Hg)	Combustor-inlet total temperature T_1 (°R)	Air flow rate \dot{m}_a (lb/sec)	Air flow rate per unit area \dot{m}_a/A_n (lb/(sq ft))	Combustor reference velocity V_r (ft/sec)	Fuel flow rate \dot{m}_f (lb/hr)	Fuel manifold pressure (above combustor-inlet pressure) ΔP_f (lb/sq in.)	Fuel-air ratio f	Mean combustor-outlet temperature T_0 (°R)	Mean combustor-outlet temperature rise ΔT (°F)	Combustion efficiency η_b (percent)	Total pressure drop through combustor ΔP (in. Hg)	Combustion parameter $V_r/P_1 T_1$ (ft. lb. sec. °R units)	
30.0 gal/hr, 70° fuel atomizer; fuel, propane - concluded														
74	5.0	728	.8358	1.142	80.86	45.82	---	0.1453	1684	958	88.40	0.9785	189.2x10 ⁻⁸	
75		728	.8358	1.142	80.86	51.83	---	0.1720	1813	1085	85.06	1.014	189.2	
76		735	.8308	1.138	80.92	55.58	---	0.1858	1899	1166	85.42	1.008	188.6	
77		732	.8179	1.0985	80.77	20.88	---	0.1120	1356	826	75.01	0.5946	300.9	
78		726	.8228	1.162	80.87	34.29	---	0.1291	1472	746	76.35	0.6512	303.8	
79		726	.8218	1.148	80.81	28.56	---	0.1221	1590	854	75.15	0.6590	303.2	
80		735	.8218	1.148	81.37	32.57	---	0.1724	1724	931	78.08	0.8949	303.2	
81		728	.8228	1.162	80.97	35.44	---	0.1885	1808	1081	78.68	0.8853	303.8	
82		735	.8228	1.162	81.55	39.18	---	0.2082	1865	1132	75.24	0.8747	303.5	
83		735	.8233	1.168	81.75	42.30	---	0.2245	1778	1043	84.27	0.8587	304.0	
84	726	.8216	1.146	82.29	39.24	---	0.2420	1652	926	82.80	0.5945	315.7		
3.0 gal/hr, 50° fuel atomizer; fuel, JP-4														
85	15.0	722	1.581	2.158	79.70	35.0	8.5	0.006228	1180	458	98.23	1.580	100.6x10 ⁻⁸	
86		728	1.558	2.154	80.26	47.0	9.8	0.008379	1325	595	97.28	1.406	100.8	
87		720	1.559	2.156	79.55	52.9	11.3	0.009426	1407	687	100.8	1.432	100.7	
88		726	1.558	2.154	80.00	64.4	15.0	0.0141	1585	819	100.4	1.424	100.6	
89		722	1.585	2.141	79.80	75.8	17.0	0.01508	1644	922	99.59	1.546	100.9	
90		726	1.559	2.156	80.06	84.8	25.3	0.01613	1751	1026	96.85	1.541	100.7	
91		732	1.558	2.154	80.71	103.0	35.7	0.01836	1849	1117	98.26	1.485	100.8	
92		8.0	721	.8369	1.148	80.31	22.4	8.1	0.007454	1208	487	98.92	1.7876	189.9
93			727	.8359	1.146	80.42	26.7	9.7	0.008541	1255	528	98.41	1.7859	189.7
94			732	.8369	1.146	81.58	29.3	10.1	0.009726	1549	817	87.41	0.8421	189.8
95	732		.8349	1.144	81.27	38.2	9.4	0.01271	1524	792	87.42	0.6758	189.5	
96	728		.8340	1.142	80.41	45.4	9.6	0.01445	1618	893	87.45	0.7788	189.2	
97	726		.8350	1.141	80.41	49.7	10.7	0.01657	1739	1015	87.87	0.8926	189.1	
98	740		.8320	1.140	80.51	62.0	11.7	0.02070	1817	1088	78.52	0.8837	189.8	
99	725		.8345	1.145	80.21	69.7	15.0	0.02321	1806	1083	68.56	0.8108	189.4	
100	5.0		726	.8233	1.168	81.32	20.3	9.7	0.01077	1202	474	80.38	0.4888	304.0
101			727	.8245	1.182	81.32	24.8	9.7	0.01314	1268	541	57.02	0.5058	304.8
102		722	.8243	1.182	80.66	31.8	10.1	0.01685	1352	610	50.78	0.5077	304.6	
103		726	.8245	1.182	81.12	40.9	10.8	0.02167	1458	727	48.05	0.4996	304.6	
104		730	.8223	1.185	81.22	44.2	9.5	0.02351	1404	674	41.17	0.5590	303.6	
105		730	.8223	1.185	81.22	50.0	---	---	---	---	---	---	---	
10.5 gal/hr, 50° fuel atomizer; fuel, JP-4														
106	15.0	750	2.0355	2.788	107.6	55.2	6.2	0.007553	1288	568	101.03	2.4405	131.4x10 ⁻⁸	
107		726	2.0308	2.782	106.8	85.0	8.4	0.008892	1376	649	100.38	2.3085	131.1	
108		724	2.0308	2.782	106.7	75.8	6.3	0.01045	1458	758	100.97	2.6688	131.4	
109		726	2.0336	2.786	106.3	86.0	6.5	0.01202	1584	842	98.20	2.7276	131.3	
110		724	2.0251	2.771	106.1	94.5	6.4	0.01298	1638	912	99.22	2.7858	130.6	
111		732	2.0338	2.786	106.5	93.3	6.5	0.01274	1621	898	99.37	2.7908	131.3	
112		725	2.0545	2.787	107.8	101.0	6.5	0.01379	1898	966	99.52	2.8439	131.4	
113		728	2.0335	2.786	107.2	118.7	6.5	0.01655	1851	1125	99.10	2.9185	131.5	
114		734	2.0275	2.777	107.7	130.5	6.4	0.01789	1888	1221	99.51	2.9184	130.9	
115		732	2.630	3.603	145.0	72.3	---	0.007638	1257	525	93.70	4.611	169.6	
116	15.05	728	2.633	3.807	144.3	82.4	---	0.009748	1392	684	94.02	4.803	170.0	
117		731	2.625	3.593	---	110.5	---	0.01170	1522	791	94.56	---	169.3	
118		750	2.625	3.696	---	132.7	---	0.01404	1630	900	90.78	---	169.5	
119		725	2.623	3.683	---	149.0	---	0.01578	1852	929	83.80	---	169.3	
120		725	2.628	3.597	---	188.8	---	0.01785	1583	840	67.05	---	169.5	
121		734	2.623	3.593	---	188.8	---	0.02000	1502	768	54.92	---	169.2	
30.0 gal/hr, 70° fuel atomizer; fuel, propane														
122	15.0	726	2.029	2.779	106.5	51.78	---	0.007087	1266	540	87.70	2.894	131.0x10 ⁻⁸	
123		734	2.027	2.777	107.5	57.98	---	0.007943	1356	622	101.2	2.907	130.9	
124		750	2.050	2.781	107.0	89.42	---	0.008499	1445	715	98.27	3.004	131.1	
125		720	2.029	2.779	106.8	81.20	---	0.01112	1627	807	95.55	3.021	131.0	
126		725	2.029	2.779	106.0	87.67	---	0.01200	1621	898	99.37	3.072	131.0	
127		732	2.050	2.781	107.3	99.32	---	0.01359	1728	986	98.47	3.118	131.1	
128		724	2.029	2.779	106.2	106.6	---	0.01501	1824	1100	99.54	3.104	131.0	
129		734	2.029	2.779	107.6	114.9	---	0.01573	1891	1157	100.4	3.215	131.0	
130		754	2.094	3.553	---	64.27	---	0.008893	1296	552	102.9	---	167.4	
131		15.1	732	2.606	3.570	---	78.06	---	0.008520	1351	619	96.24	---	168.0
132	750		2.607	3.571	---	98.72	---	0.01031	1489	739	93.89	---	165.9	
133	752		2.619	3.588	---	108.5	---	0.01161	1569	837	96.22	---	168.5	
134	722		2.617	3.585	---	116.5	---	0.01257	1612	890	95.56	---	165.2	
80.0 gal/hr, 70° fuel atomizer; fuel, propane														
135	15.0	729	2.622	3.592	145.2	80.18	---	0.008498	1577	848	98.82	---	169.3x10 ⁻⁸	
136		727	2.624	3.595	141.8	100.8	---	0.01120	1551	824	97.08	---	167.2	
137		727	2.612	3.578	137.9	130.9	---	0.01392	1727	1000	96.53	---	160.0	
138		726	2.618	3.588	137.1	156.9	---	0.01886	1887	1131	92.75	---	164.3	
139		724	2.601	3.565	138.2	180.3	---	0.01925	1854	1130	80.71	---	162.5	
140		728	2.591	3.549	---	192.5	---	0.02064	1918	1190	79.94	---	156.6	
141		726	2.607	3.571	---	198.6	---	0.02116	1851	1125	75.58	---	163.9	
142		722	2.621	3.590	142.2	---	---	---	---	---	---	3.074	169.2	
143		728	2.0549	2.788	108.7	---	---	---	---	---	---	1.682	131.4	
144		751	1.8549	1.144	80.92	---	---	---	---	---	---	0.5284	188.5	
145		751	.8226	1.159	81.42	---	---	---	---	---	---	0.5960	303.7	

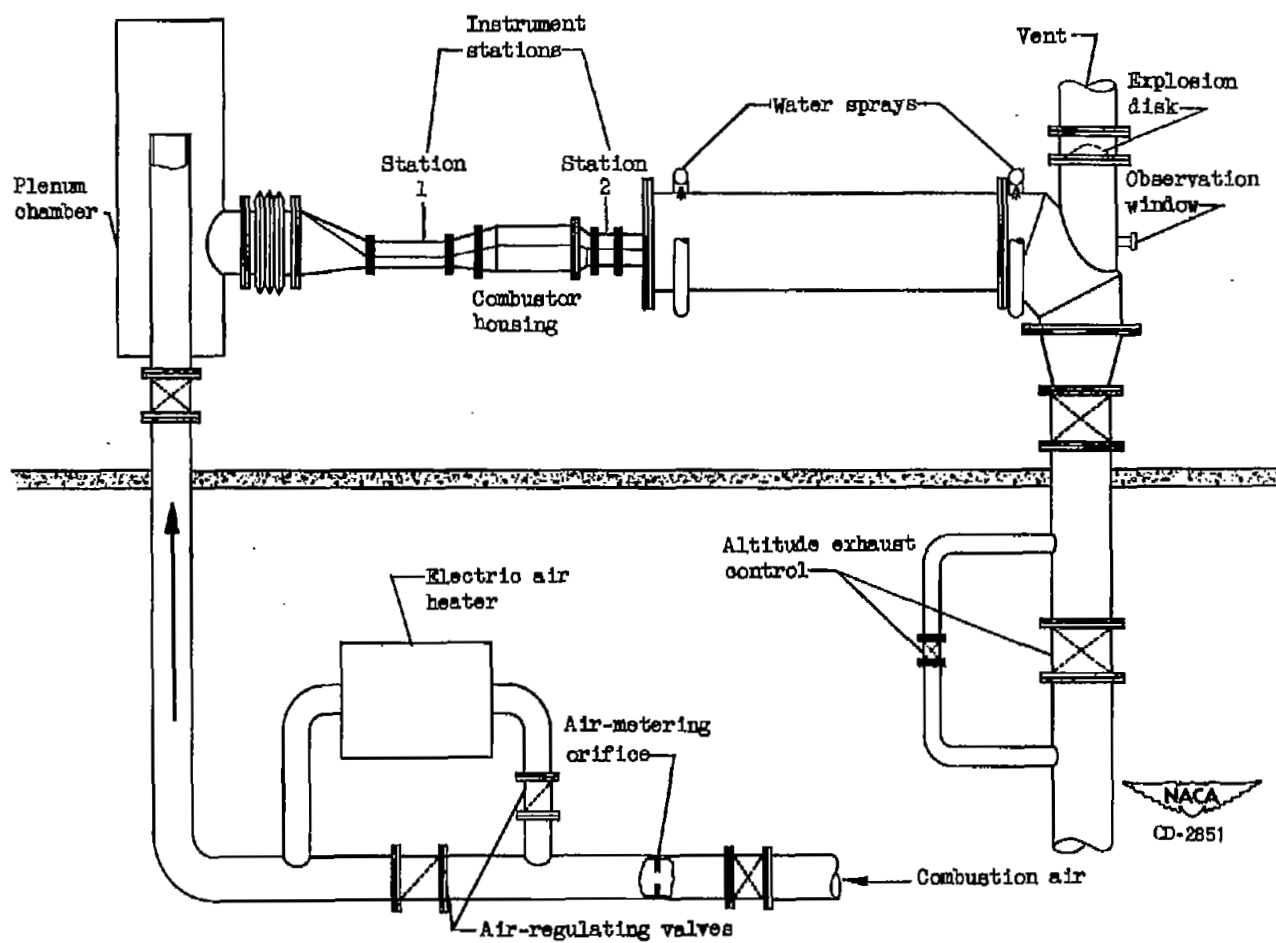
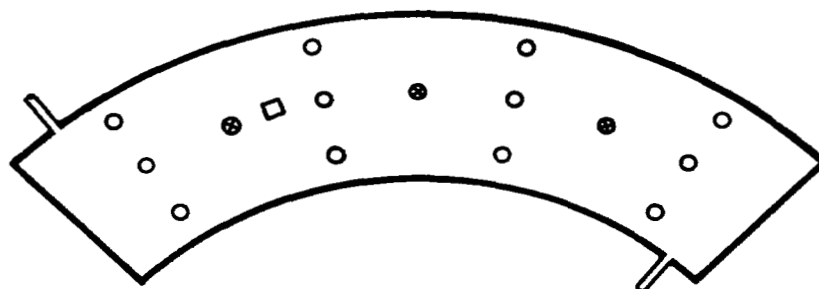


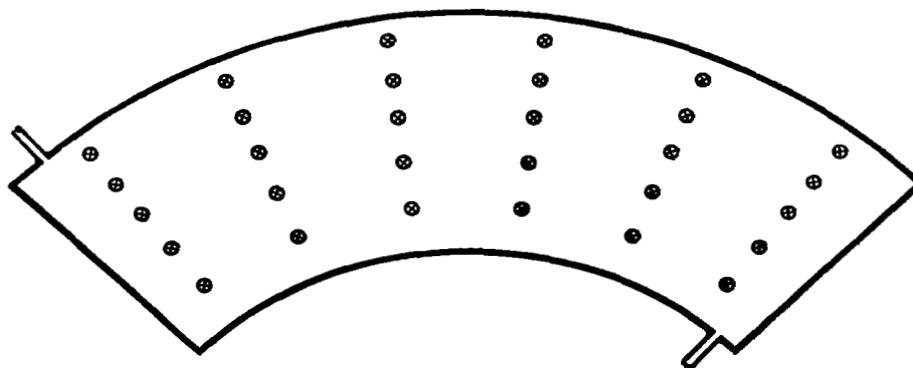
Figure 1. - Installation of one-quarter sector of 25 $\frac{1}{2}$ -inch-diameter annular combustor.



(a) Inlet thermocouples (iron-constantan), inlet total-pressure rakes, and stream-static probe in plane at station 1.

- ⊗ Thermocouple
- Total-pressure rake
- └└ Static-pressure orifice
- Stream-static probe

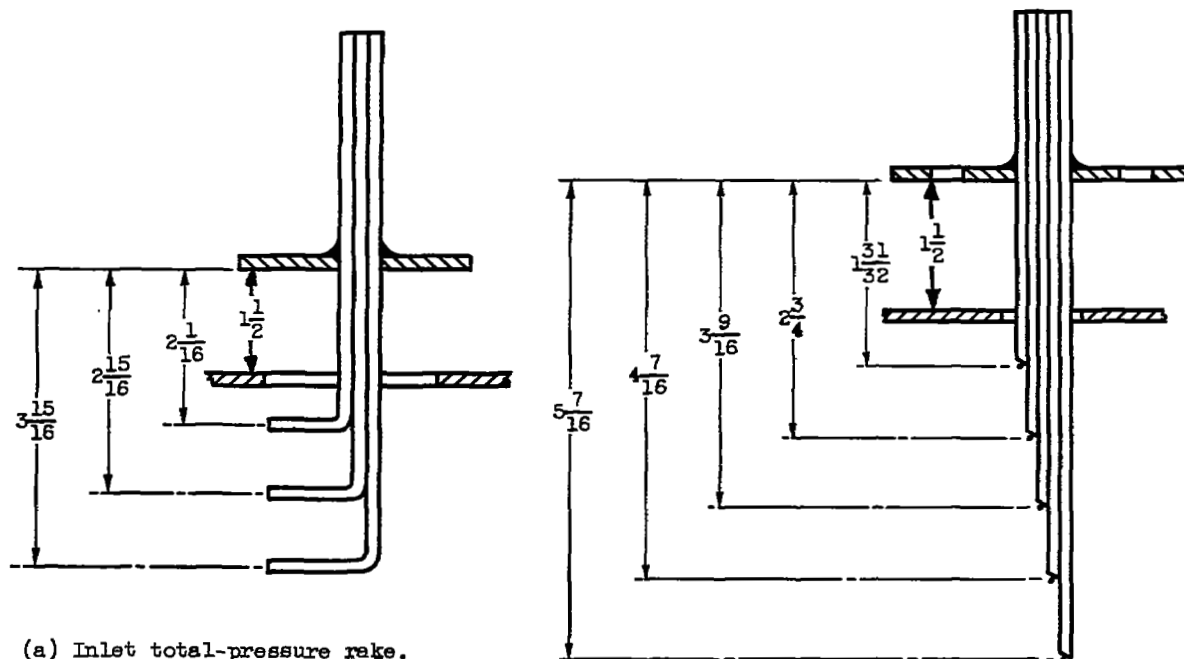
NACA
CD-2845



(b) Outlet thermocouples (chromel-alumel) in plane at station 2.

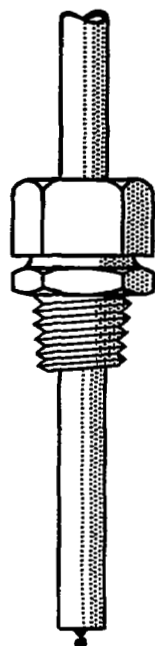
Figure 2. - Locations of instrumentation.

2709

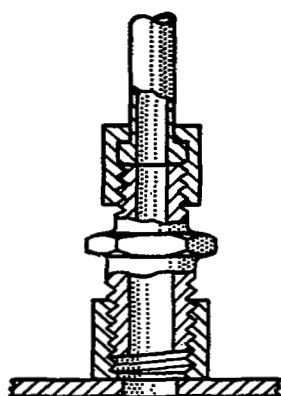


(a) Inlet total-pressure rake.

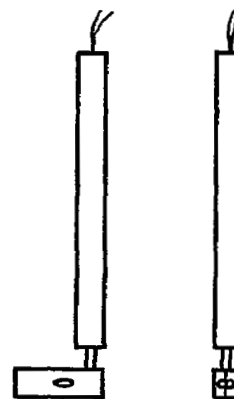
(b) Outlet thermocouple rake.



(c) Inlet thermocouple.



(d) Static-pressure orifice.



(e) Wedge stream-static probe.



CD-2846

Figure 3. - Details of instrumentation. (Dimensions are in inches.)

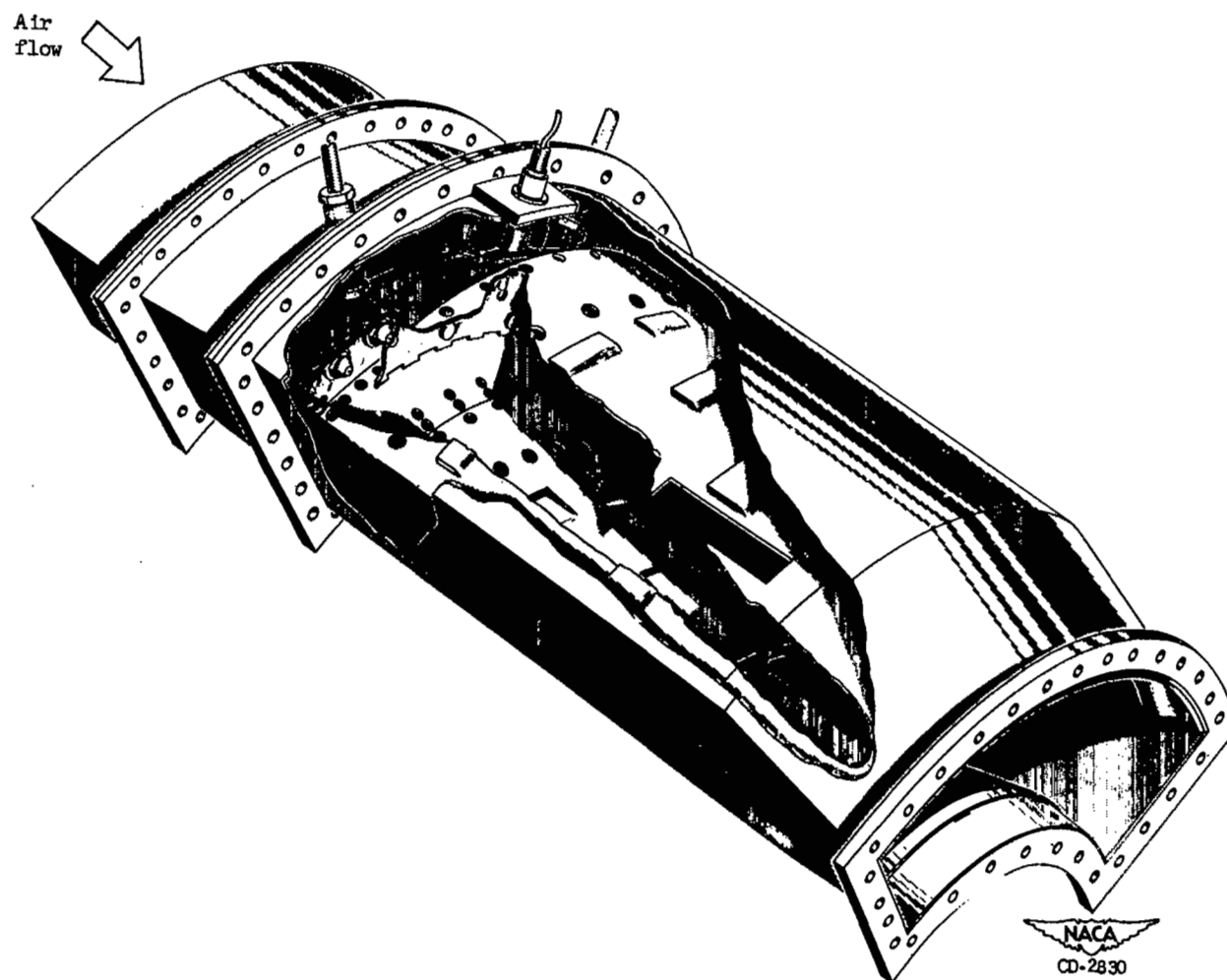


Figure 4. - One-quarter sector of model 13 annular combustor assembled in test ducting.

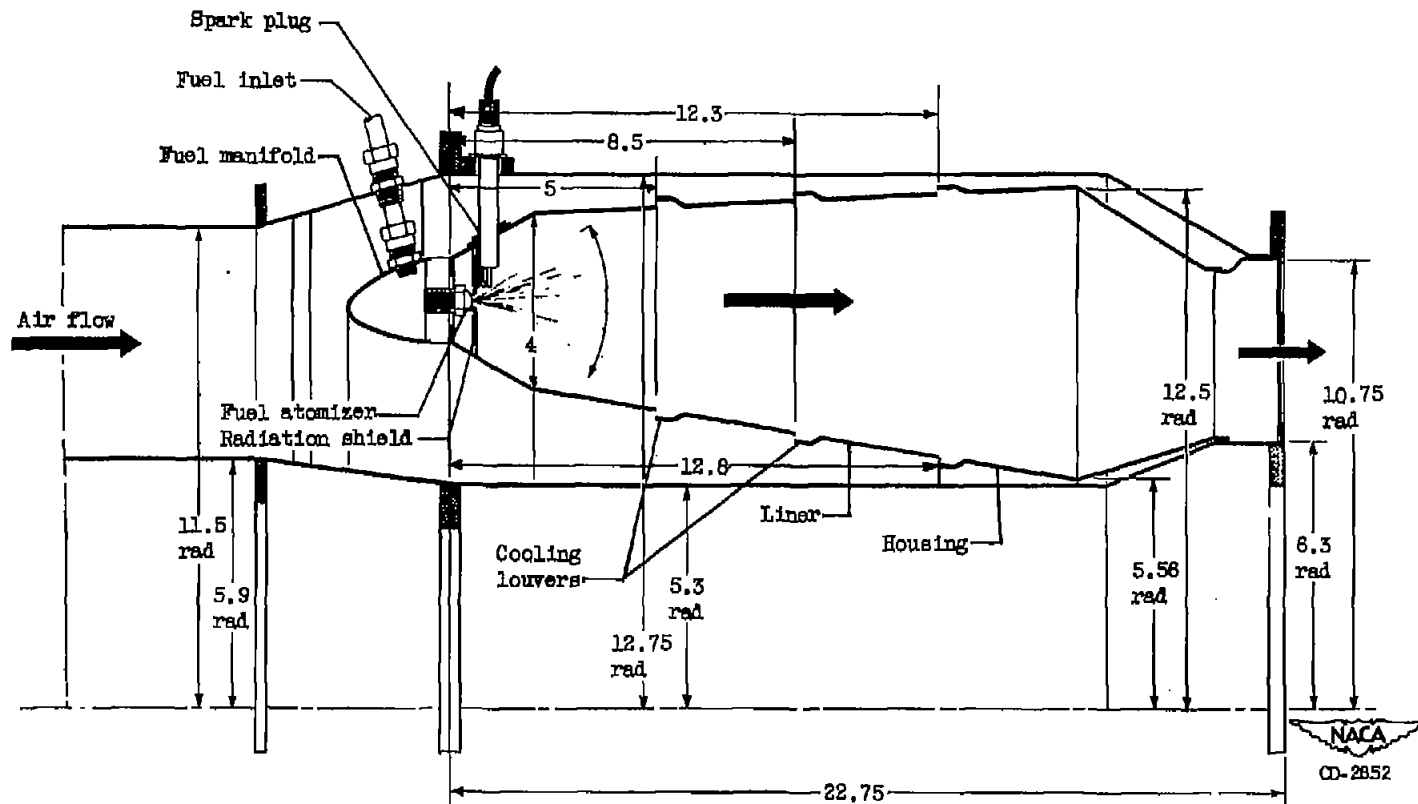


Figure 5. - Longitudinal cross-sectional view of combustor and housing. (Dimensions are in inches.)

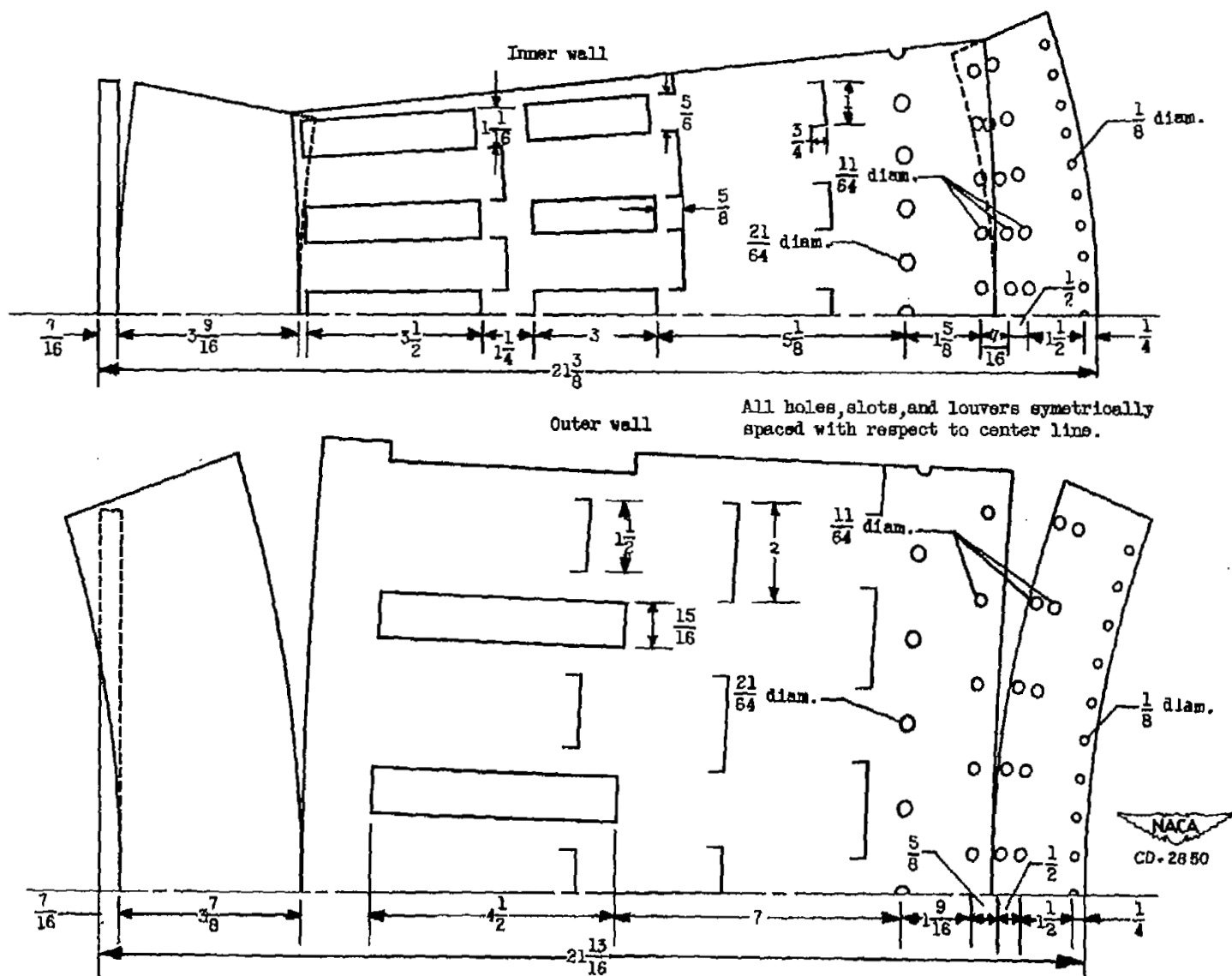


Figure 6. - One-eighth sector developed view of liner walls of combustor model 13. (Dimensions are in inches.)

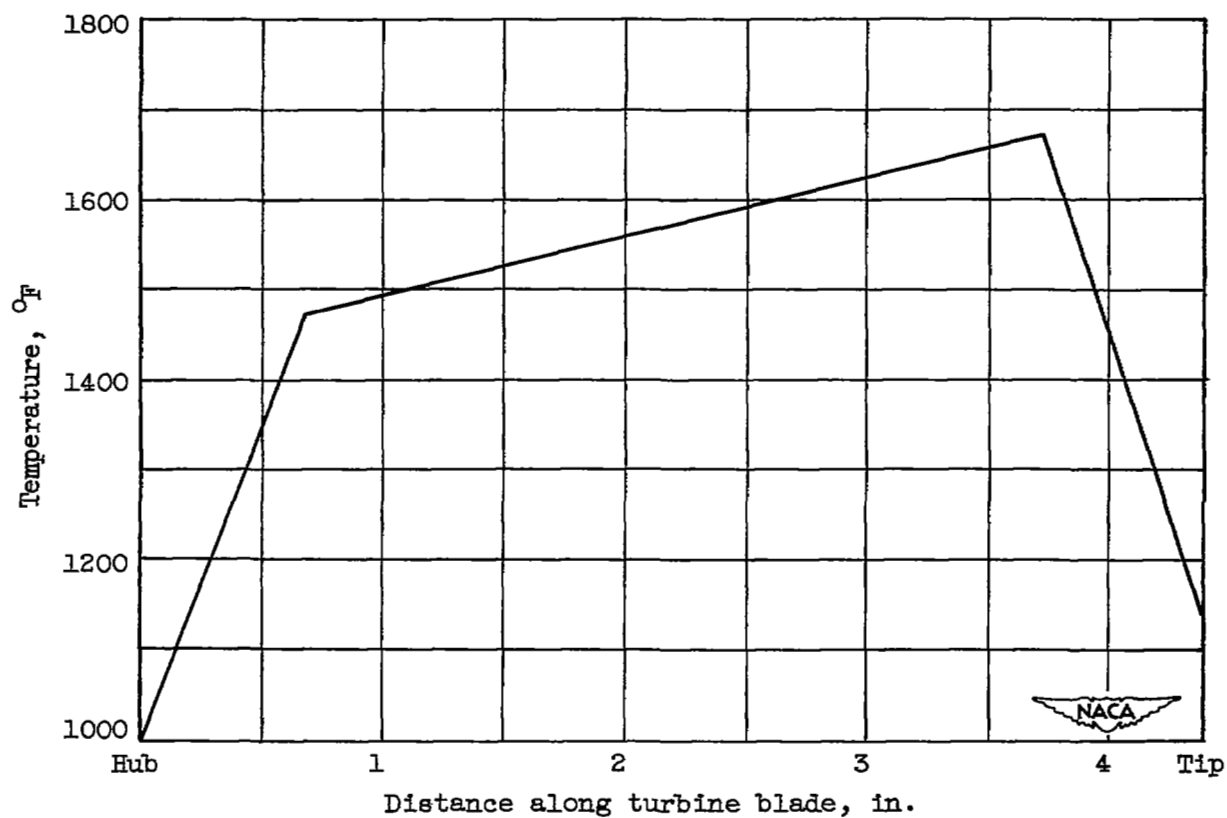


Figure 7. - Desired combustor-outlet temperature distribution.

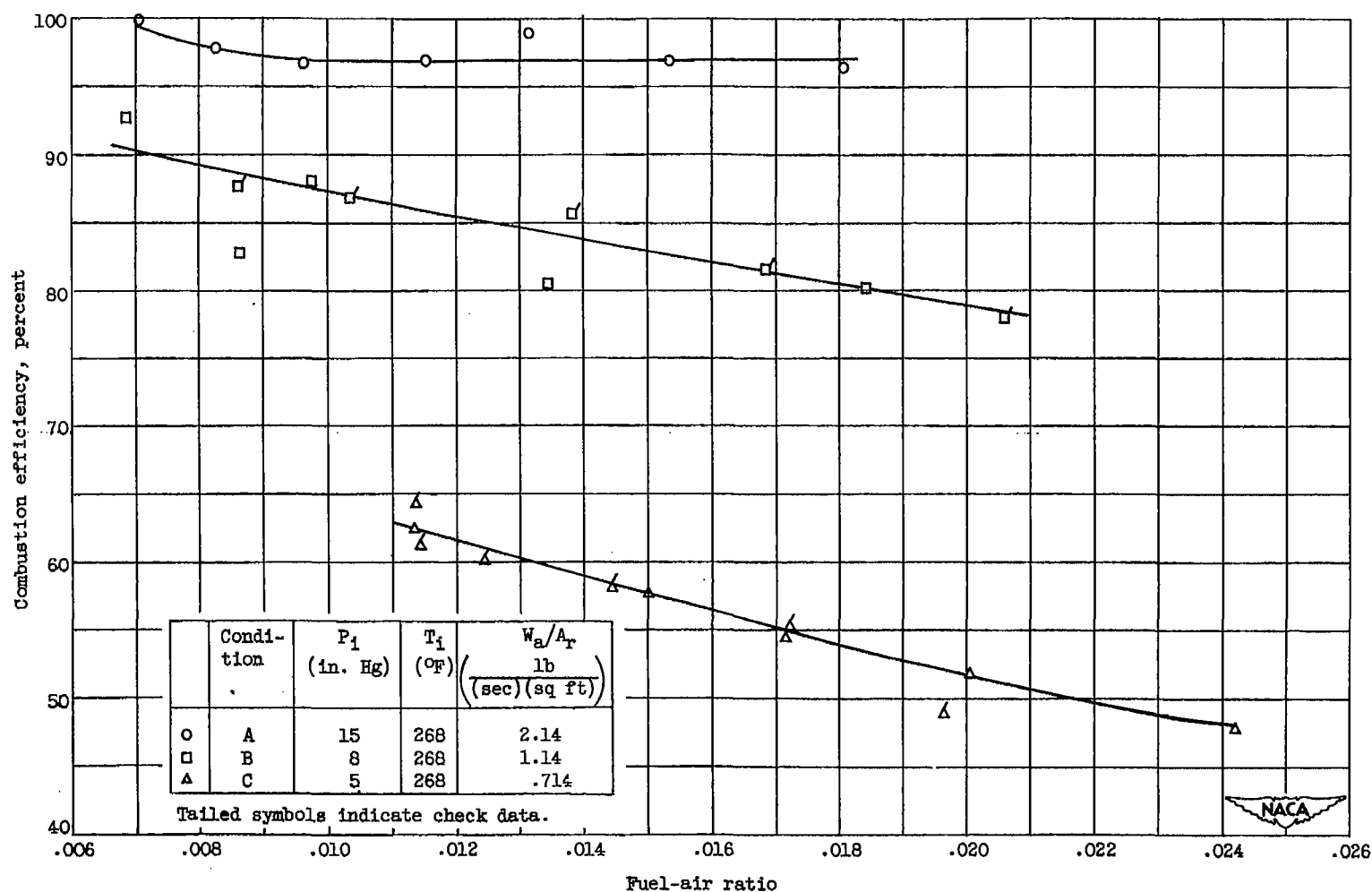


Figure 8. - Combustion efficiency of model 13 combustor with liquid MIL-F-5624A grade JP-4 fuel at various pressures. 10.5-gallon-per-hour, 60° fuel atomizers.

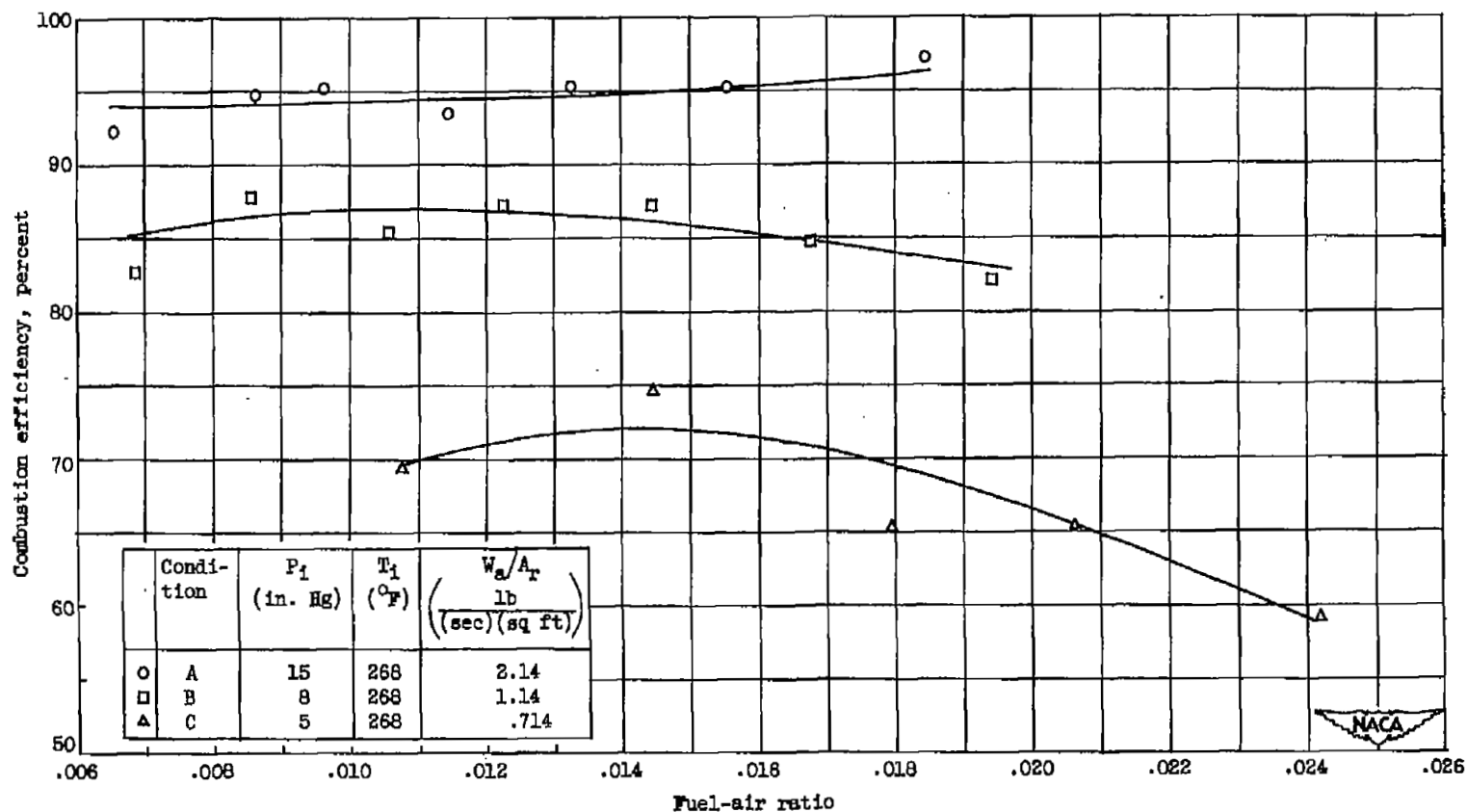


Figure 9. - Combustion efficiency of model 13 combustor with heated (300° F) MIL-F-5624A grade JP-4 fuel at various pressures. 10.5-gallon-per-hour, 60° fuel atomizers.

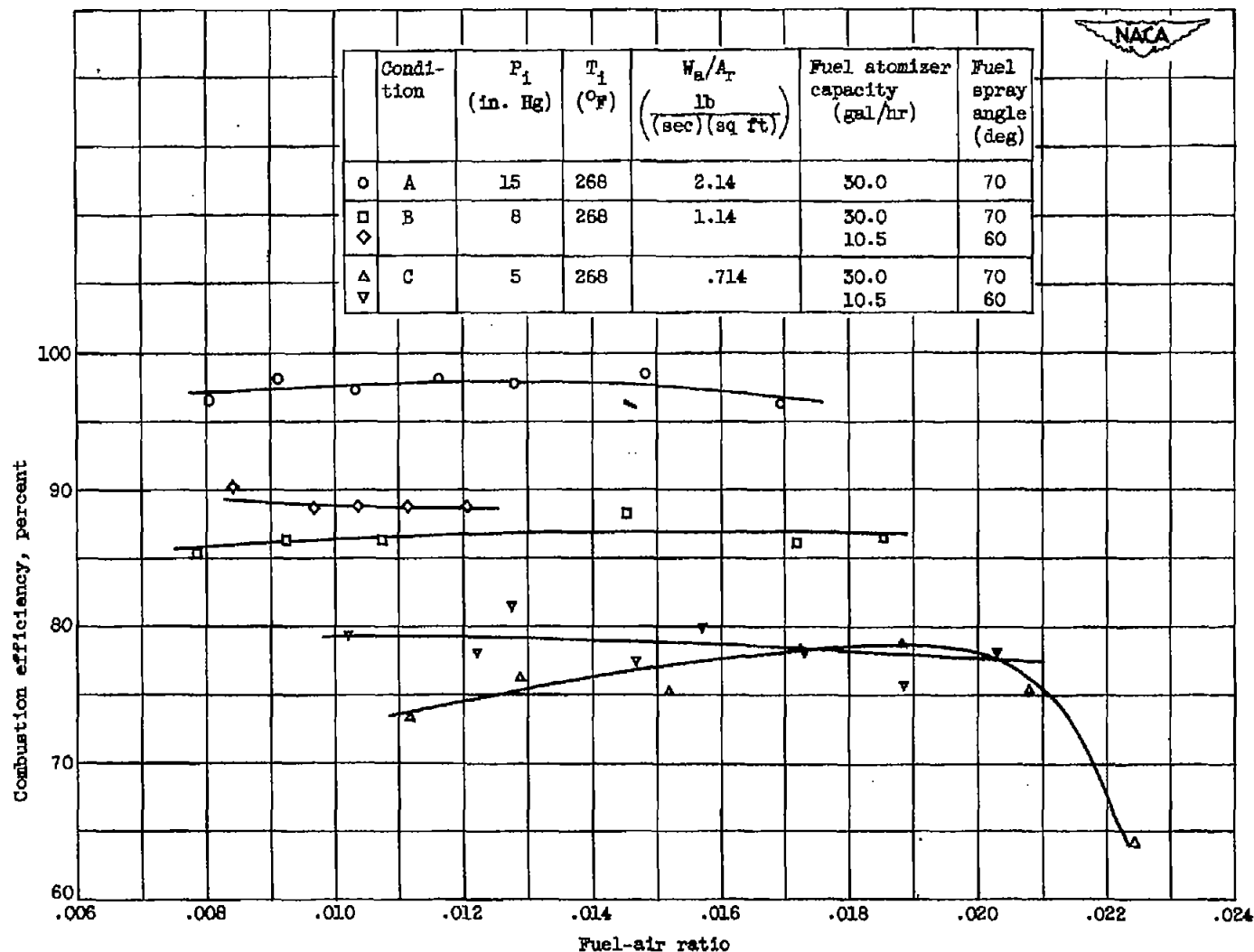


Figure 10. - Combustion efficiency of model 13 combustor with vapor (propane) fuel at various pressures. Two fuel atomizer capacities.

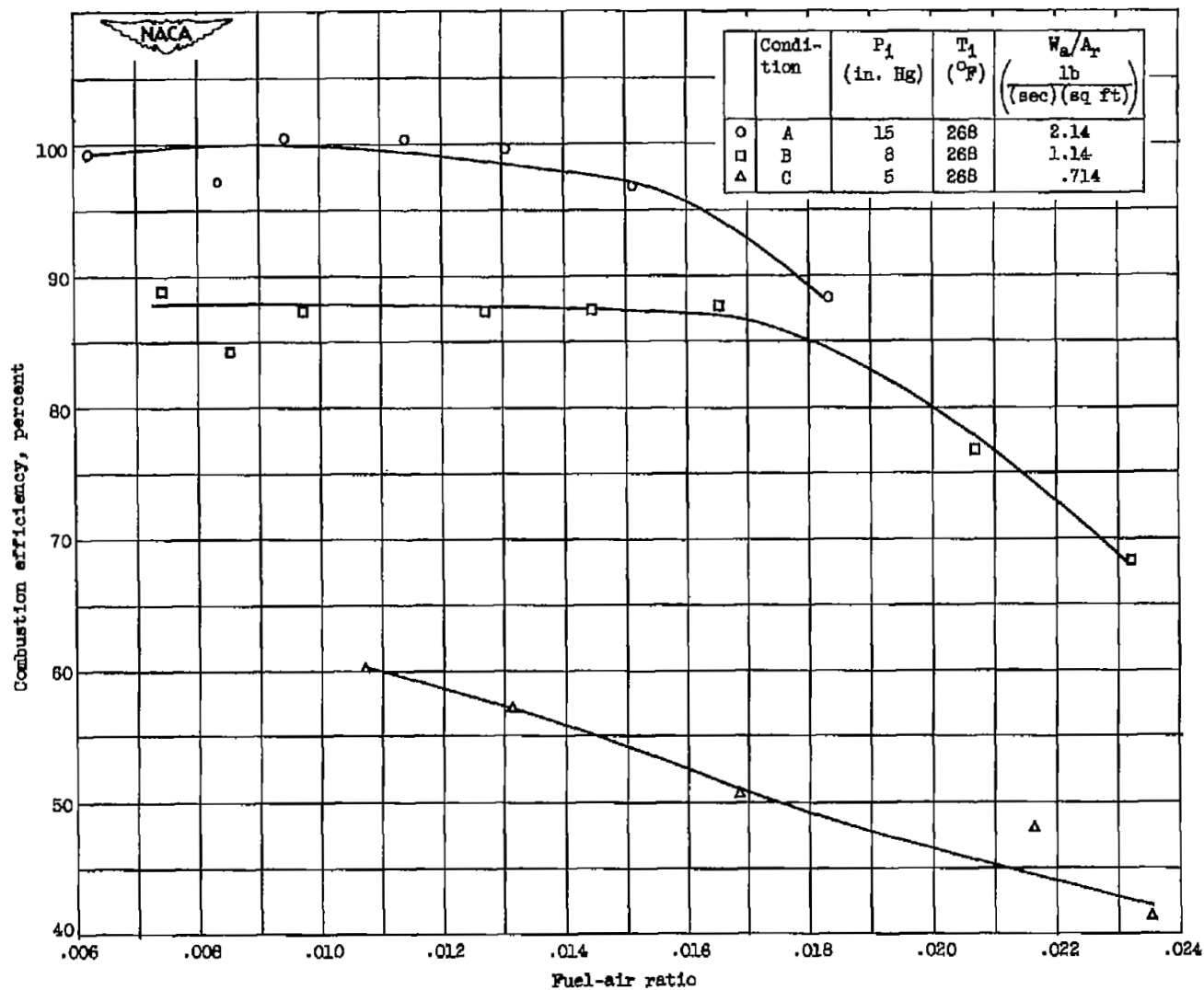


Figure 11. - Combustion efficiency of model 13 combustor with liquid MIL-F-5624A grade JP-4 fuel at various pressures. 3.0-gallon-per-hour, 60° fuel atomizers.

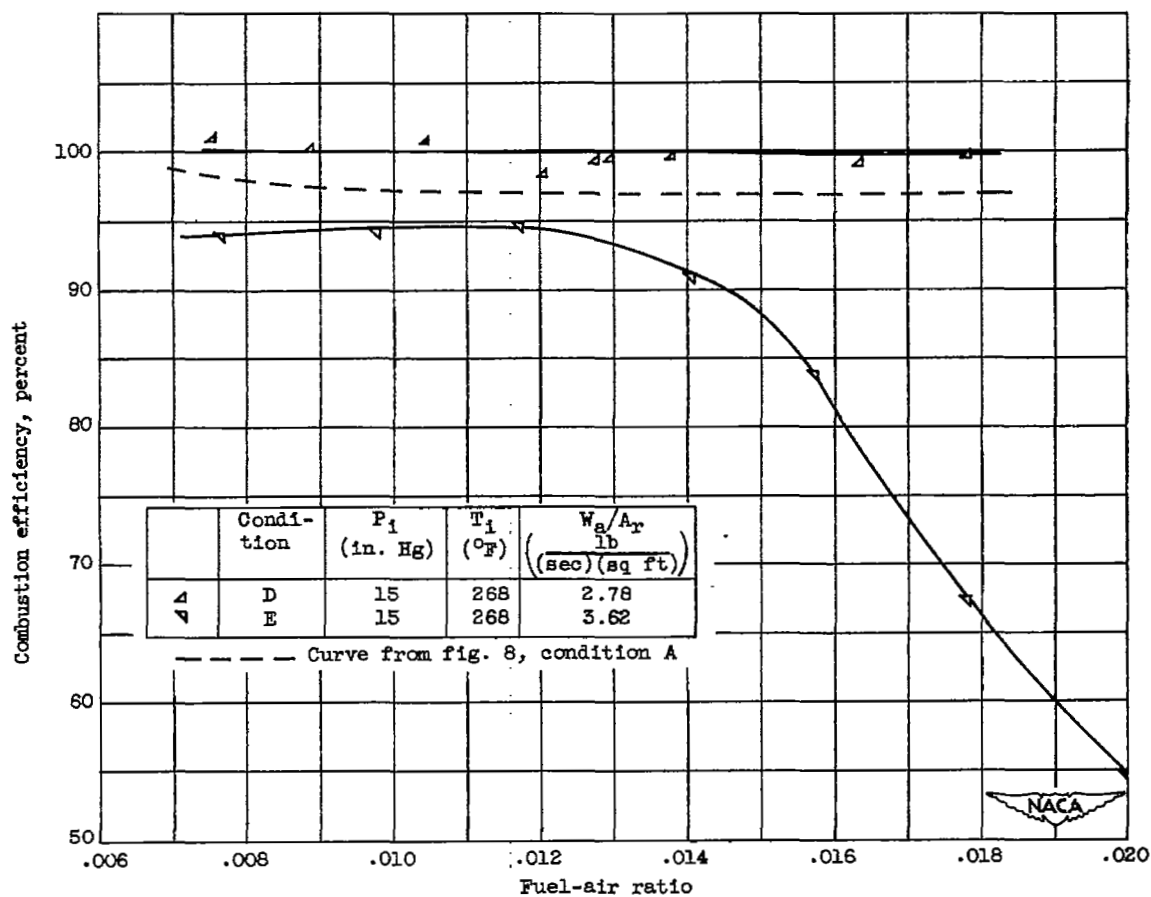


Figure 12. - Combustion efficiency of model 13 combustor with liquid MIL-F-5624A grade JP-4 fuel at various air-flow rates. 10.5-gallon-per-hour, 60° fuel atomizers.

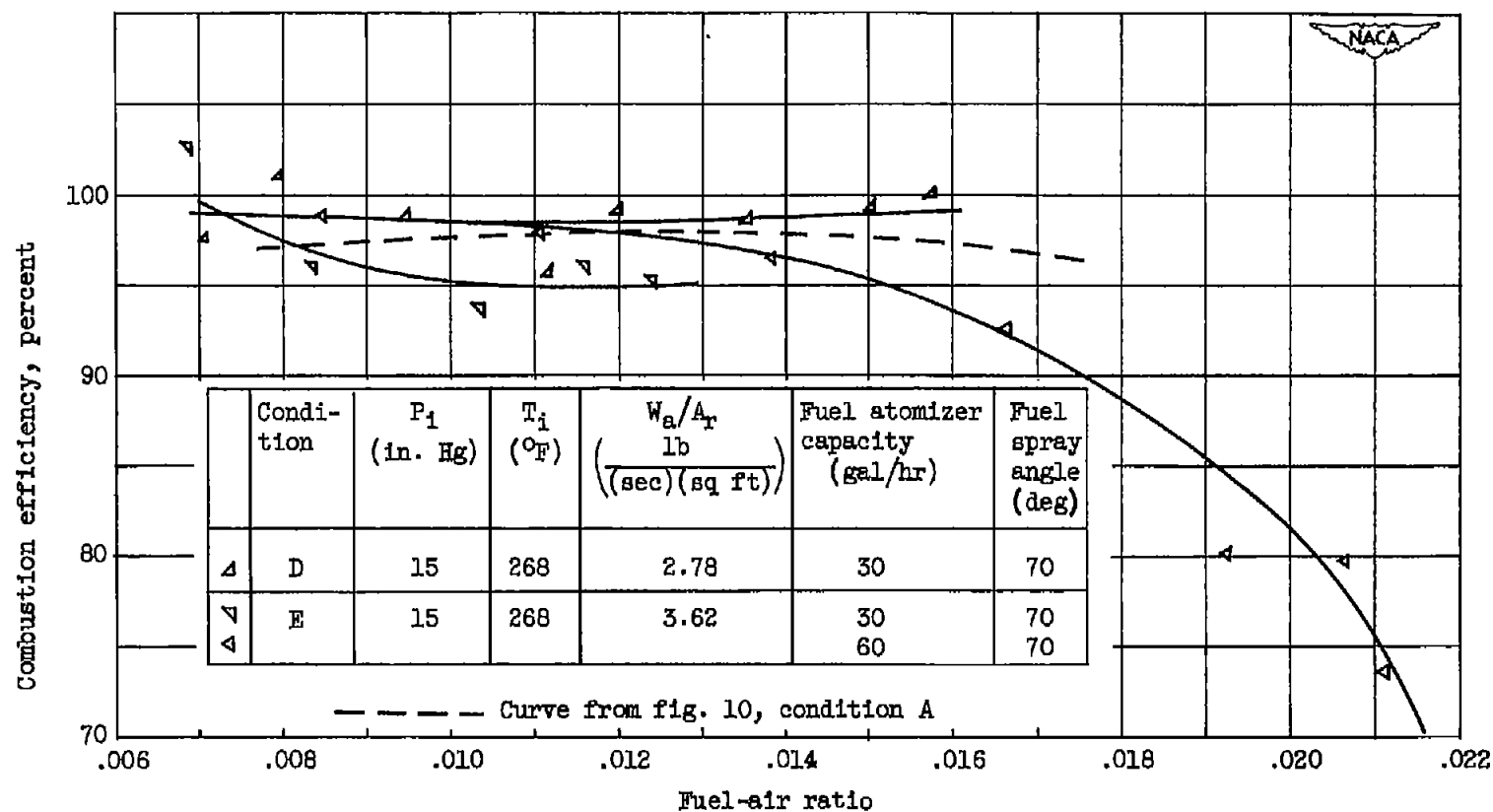


Figure 13. - Combustion efficiency of model 13 combustor with vapor (propane) fuel at various air-flow rates. Two fuel atomizer capacities.

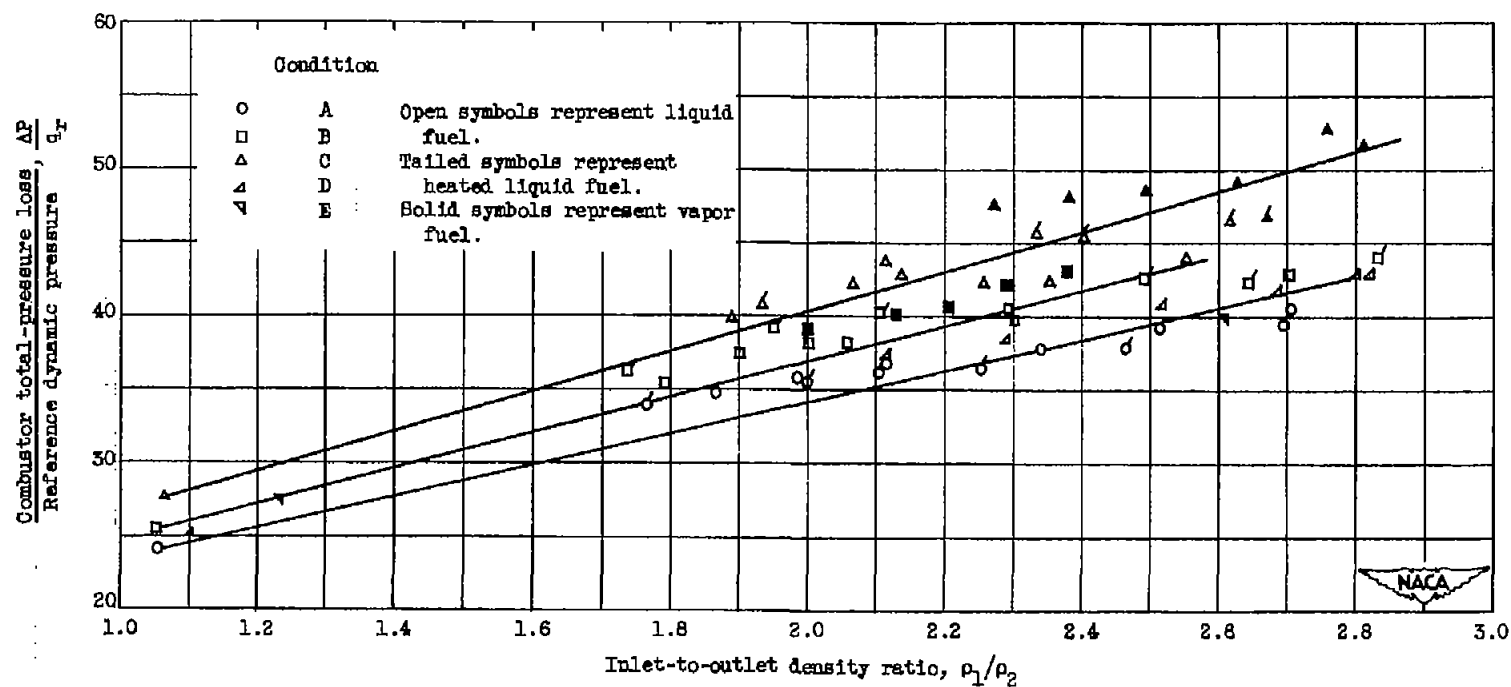
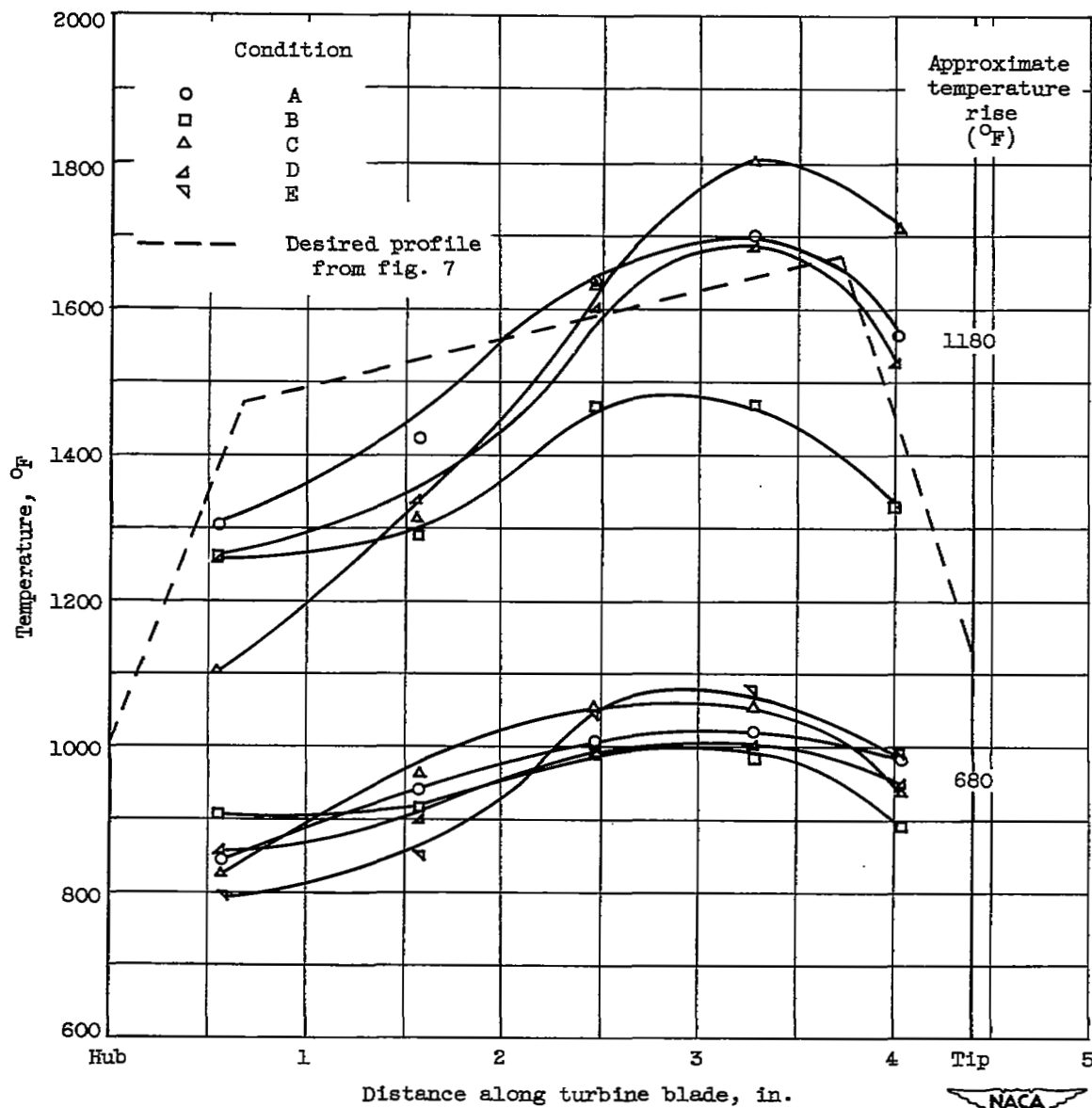
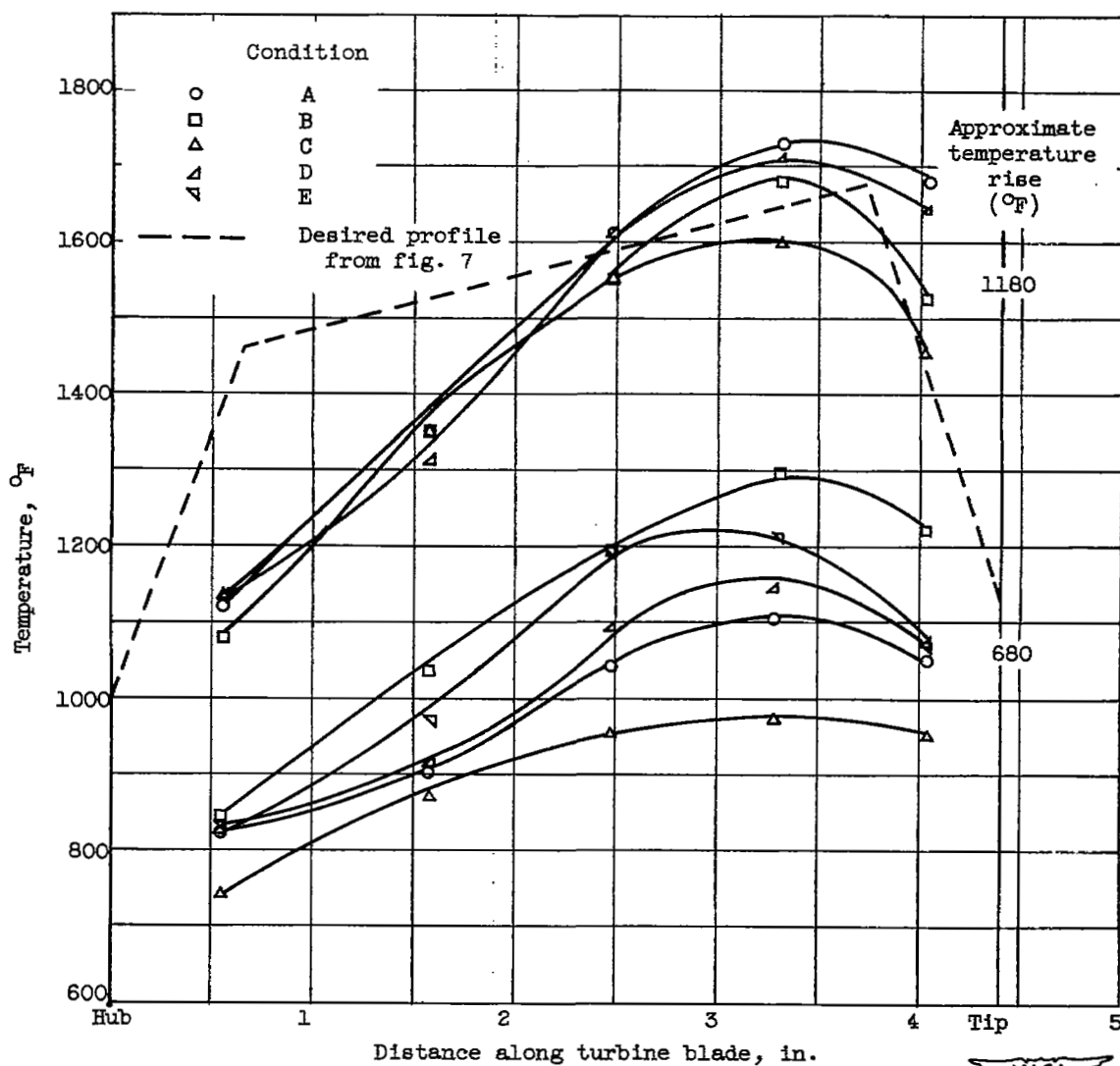


Figure 14. - Combustor pressure losses.



(a) Liquid MIL-F-5624A grade JP-4 fuel.

Figure 15. - Combustor-outlet temperature profiles.



(b) Vapor (propane) fuel.

Figure 15. - Concluded. Combustor-outlet temperature profiles.

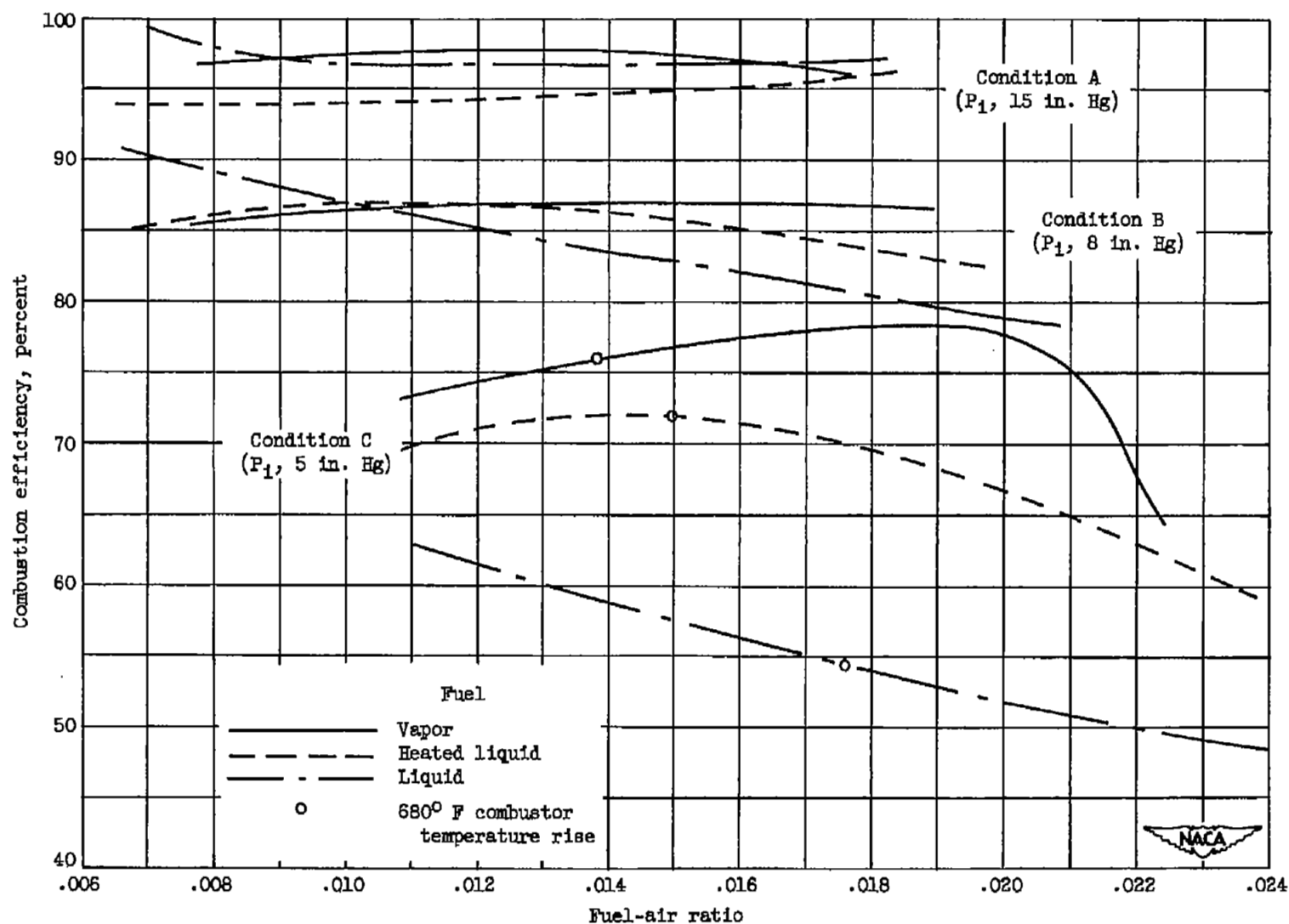
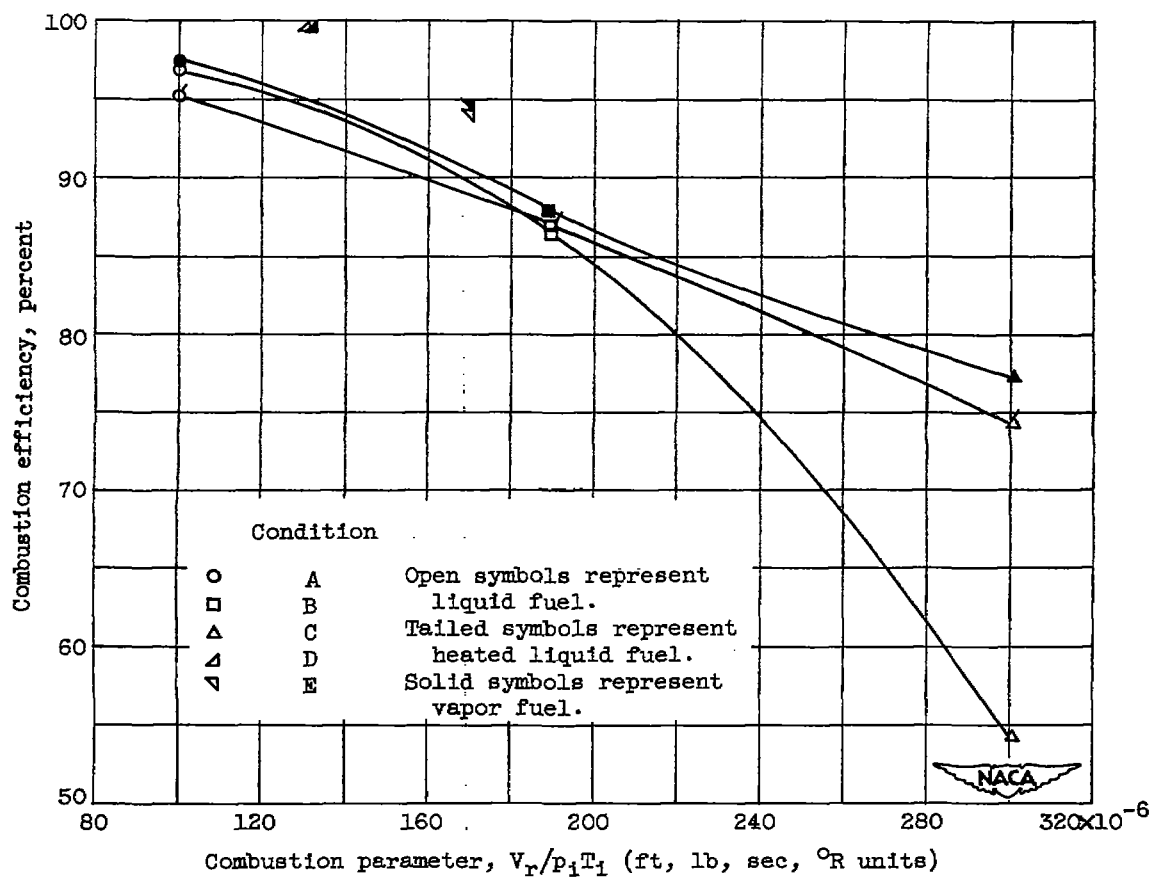
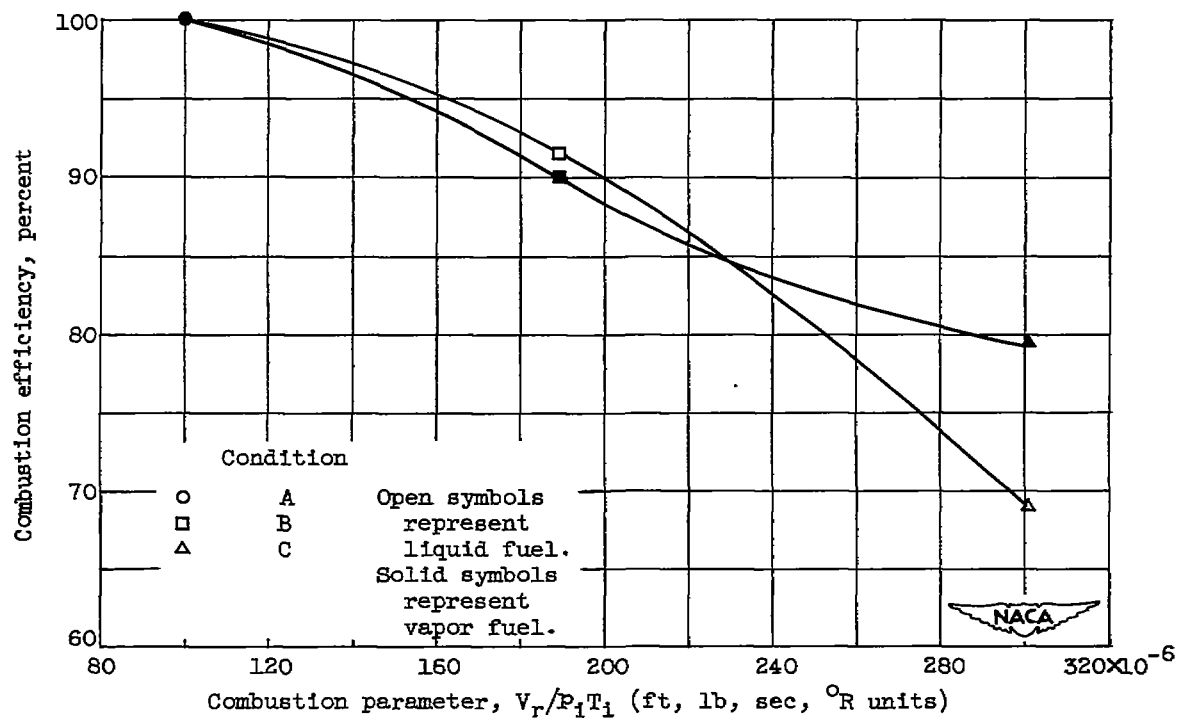


Figure 16. - Comparison of combustion efficiency for three fuel states at various pressures.



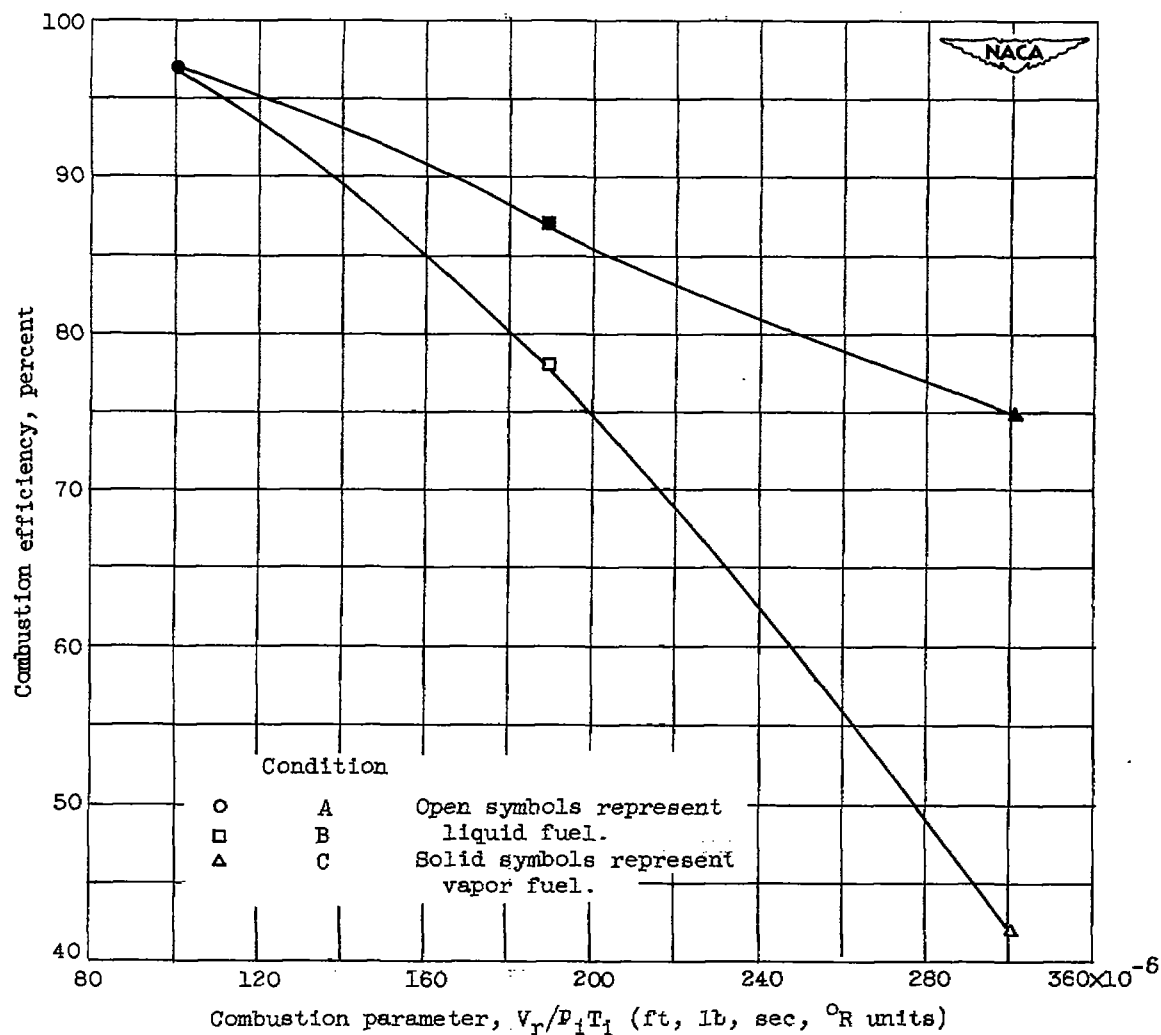
(a) Temperature rise, 680° F.

Figure 17. - Correlation of combustion efficiency data of figures 8, 9, 10, 12, and 13 with combustion parameter $V_r/p_1 T_1$.



(b) Temperature rise, $402^{\circ}F$.

Figure 17. - Continued. Correlation of combustion efficiency data of figures 10, 12, and 13 with combustion parameter $V_r/P_1 T_1$.



(c) Temperature rise, 1180° F.

Figure 17. - Concluded. Correlation of combustion efficiency data of figures 10, 12, and 13 with combustion parameter $V_r/P_1 T_1$.

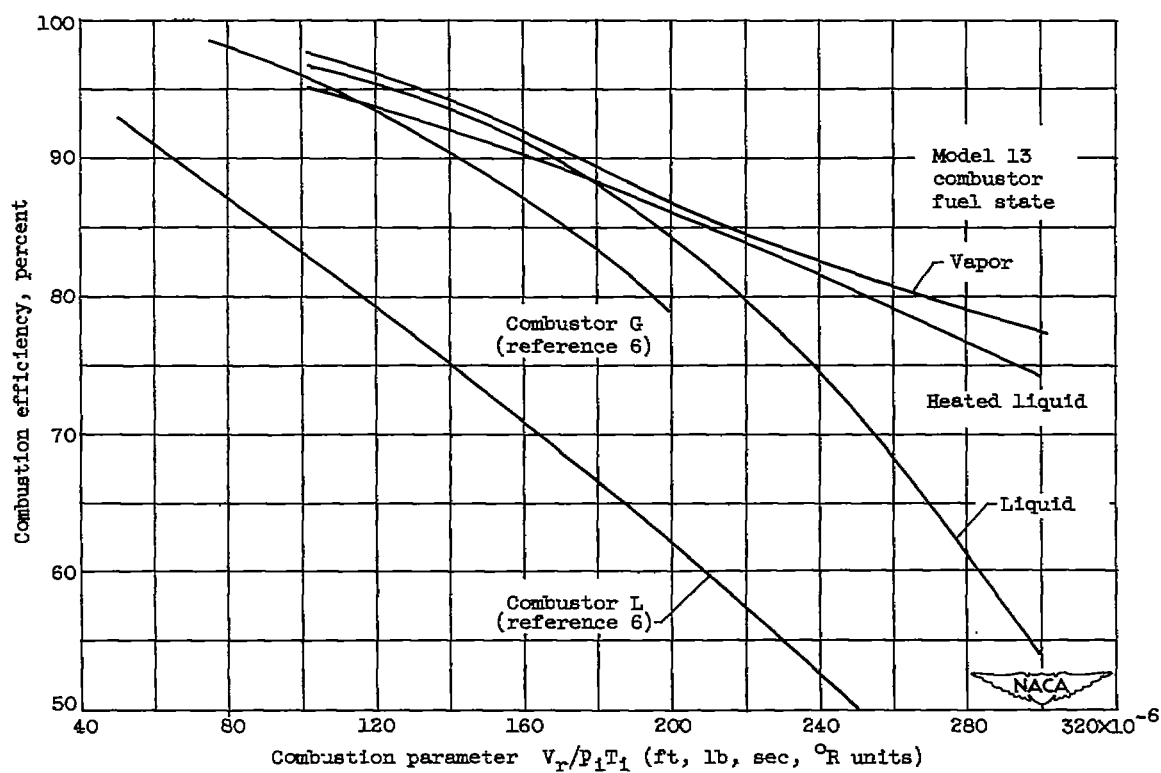
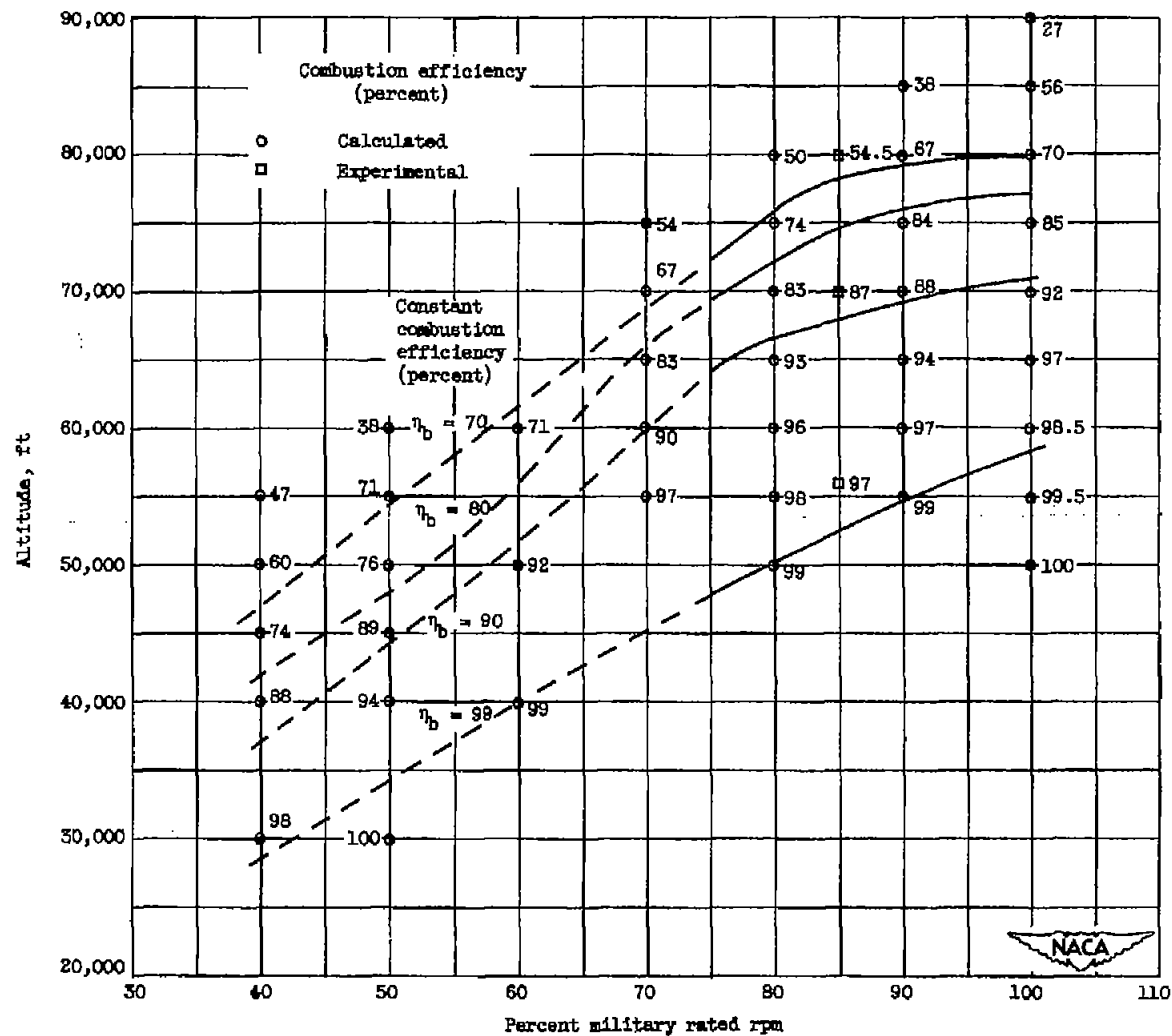
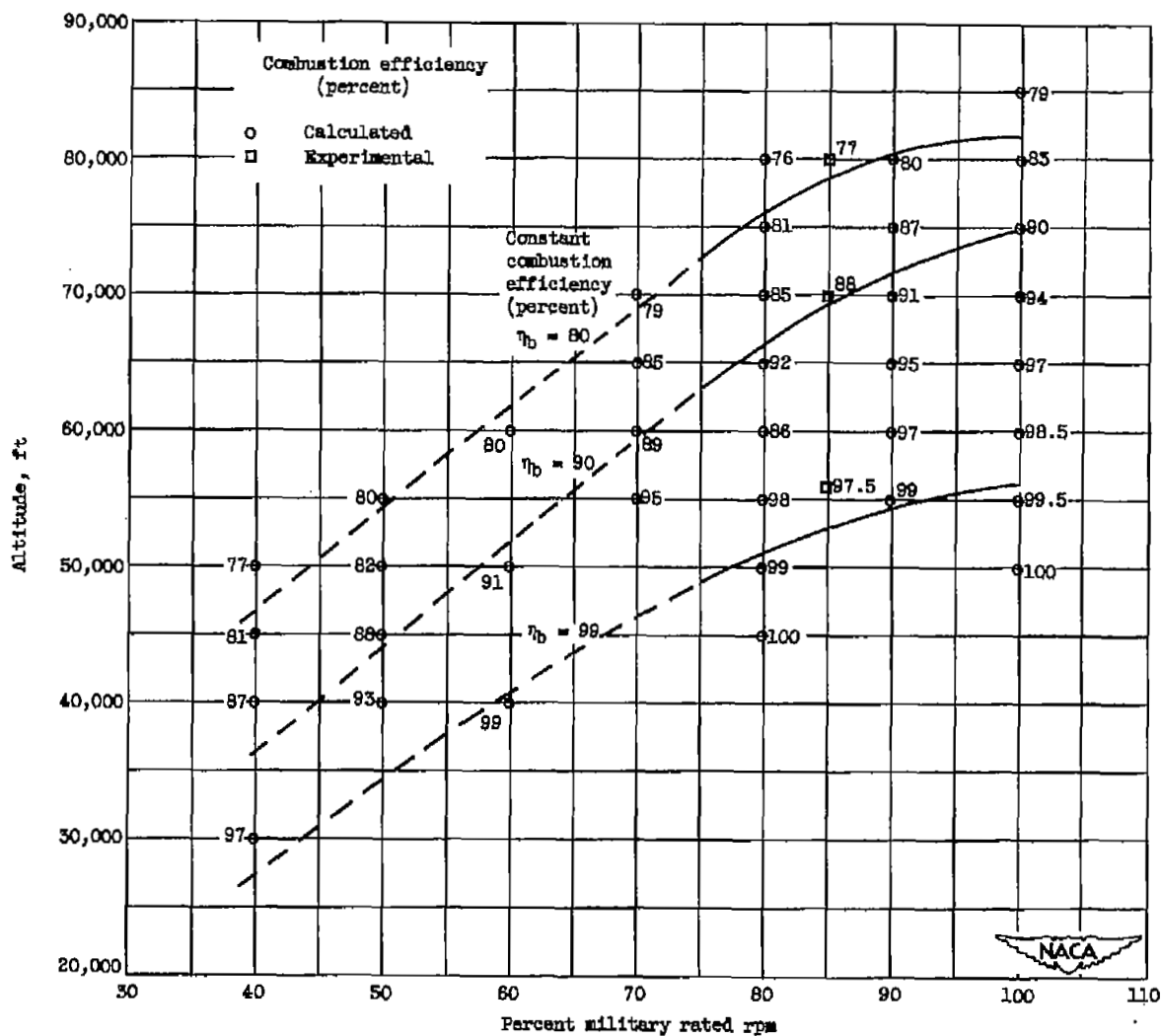


Figure 18. - Comparison of curves of figure 17 with similar curves for better combustors of reference 6.



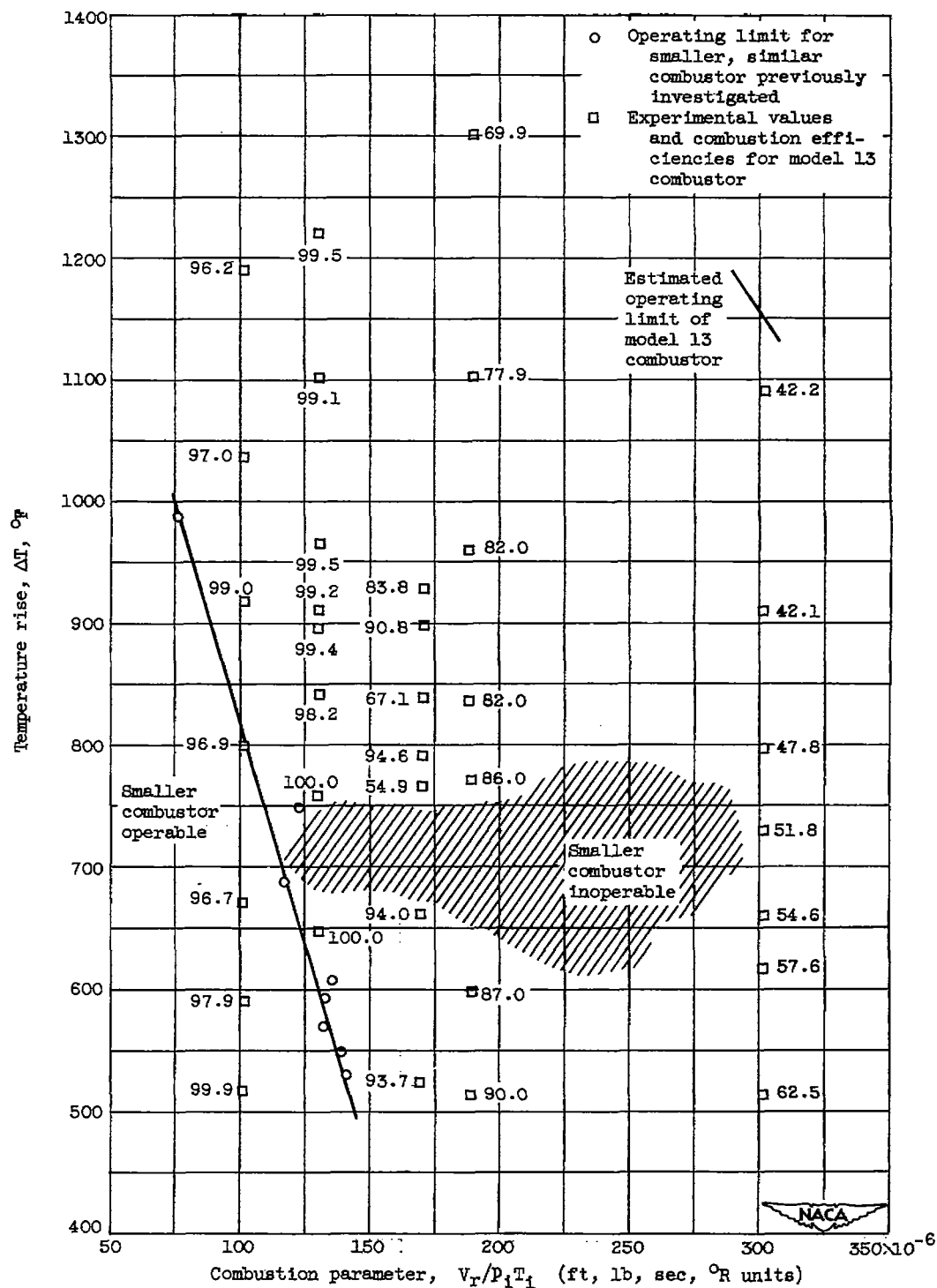
(a) Liquid MIL-F-5624A grade JP-4 fuel.

Figure 19. - Estimated altitude flight performance of model 13 combustor in 5.2 pressure ratio engine at flight Mach number 0.8.



(b) Vapor (propane) fuel.

Figure 19. - Concluded. Estimated altitude flight performance of model 13 combustor in 5.2 pressure ratio engine at flight Mach number 0.6.



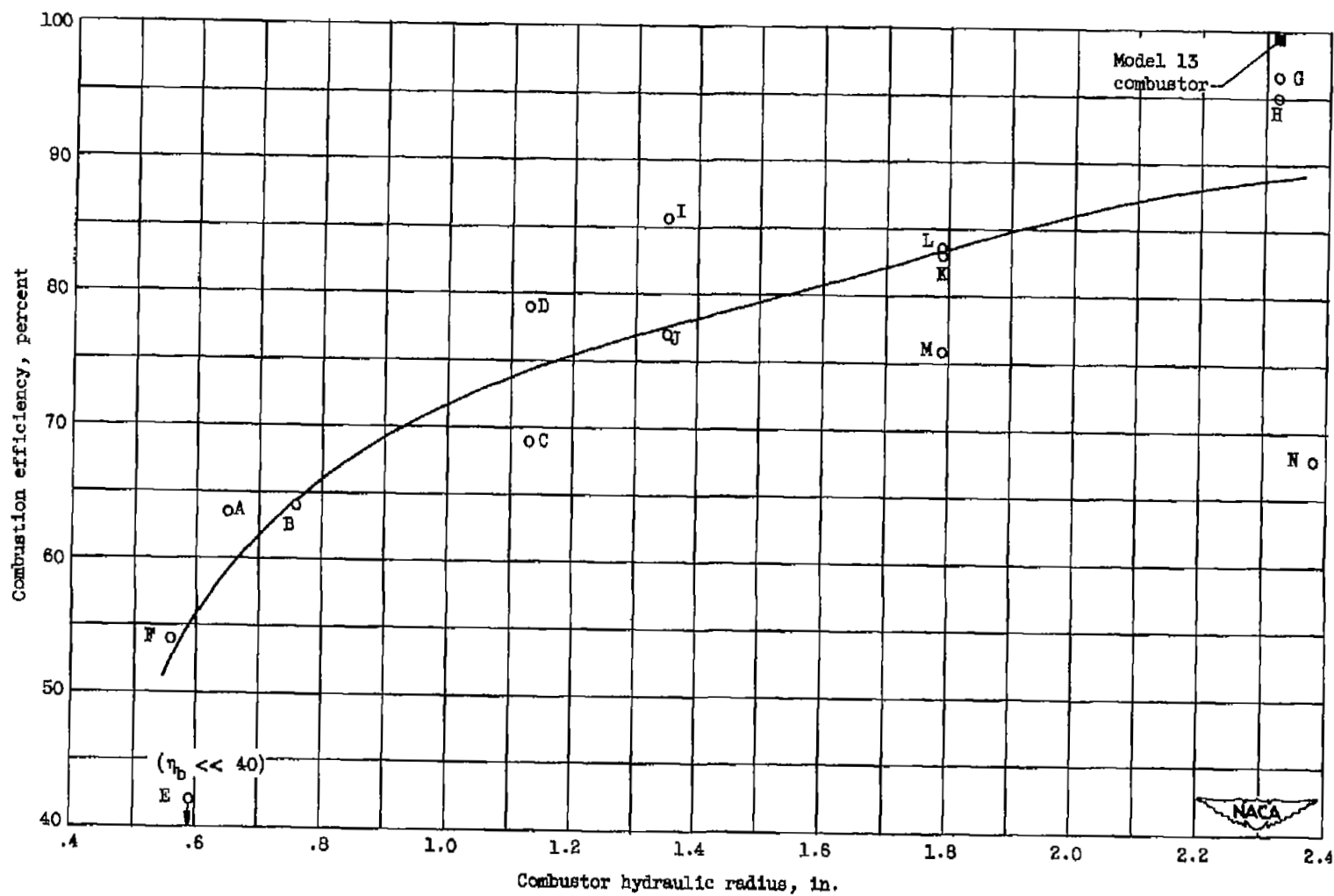
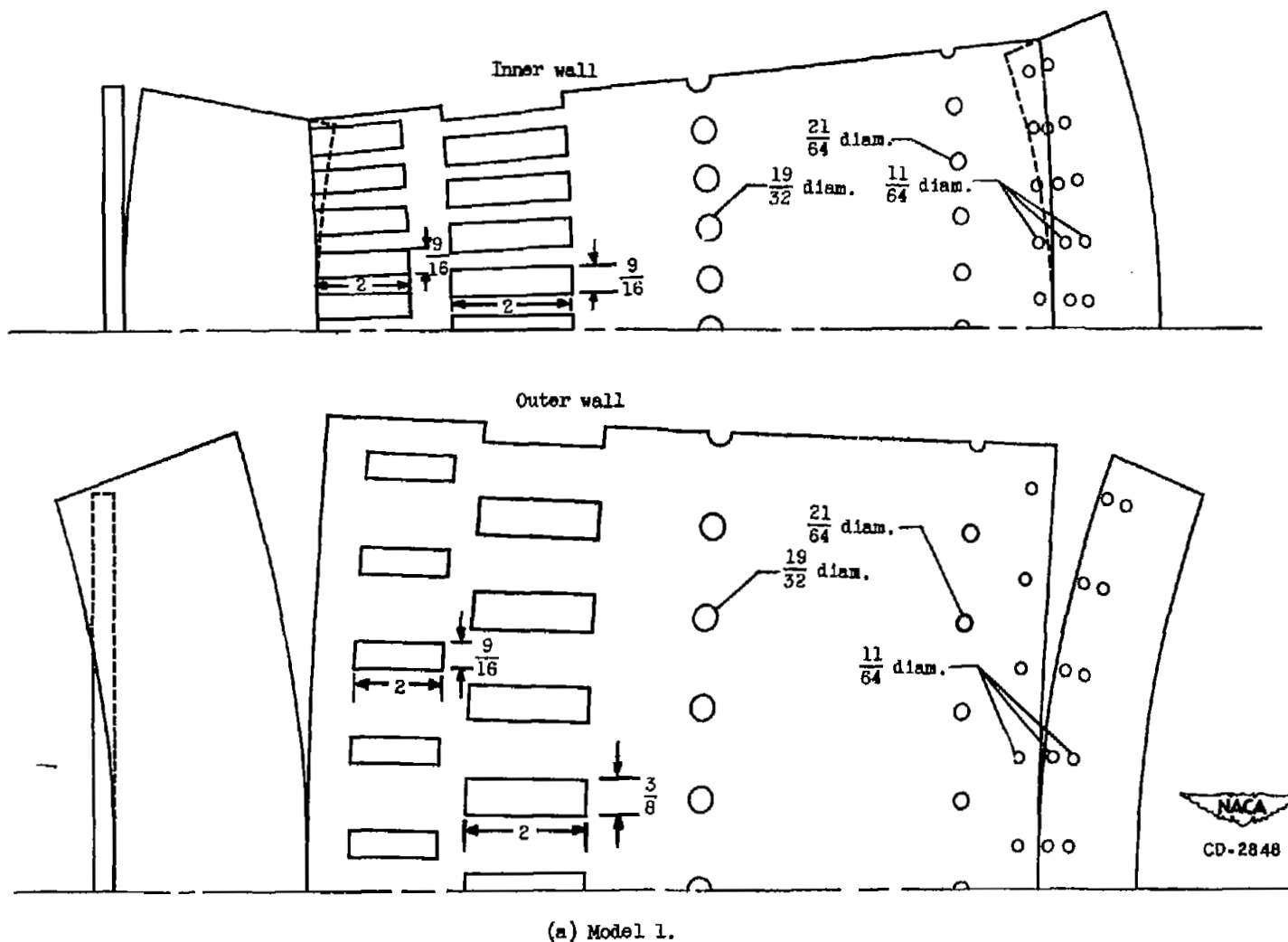
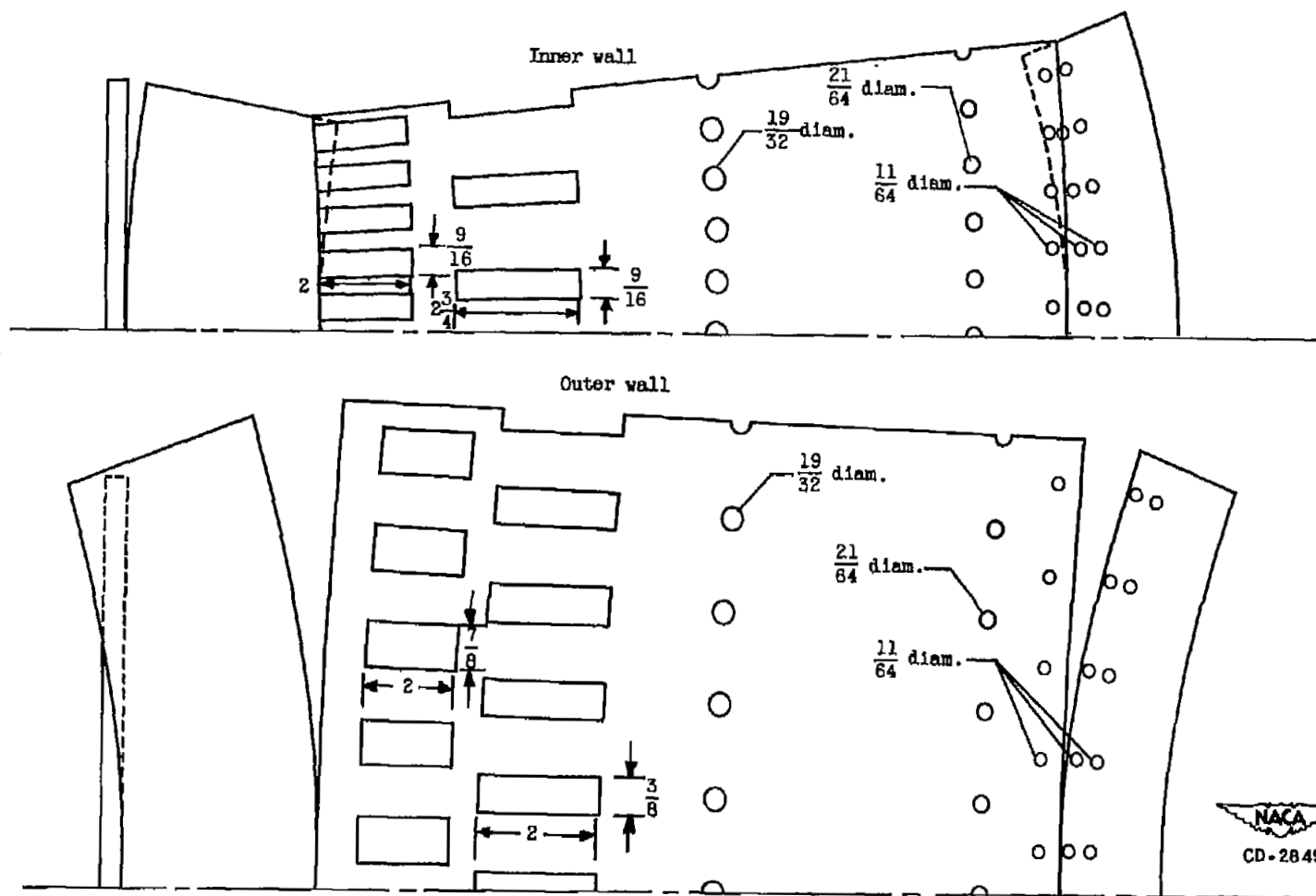


Figure 21. - Variation of combustion efficiency with combustor size at operating conditions of equal severity ($V_r/P_1T_1 = 100 \times 10^{-6}$). Letters designate various combustors of reference 6.



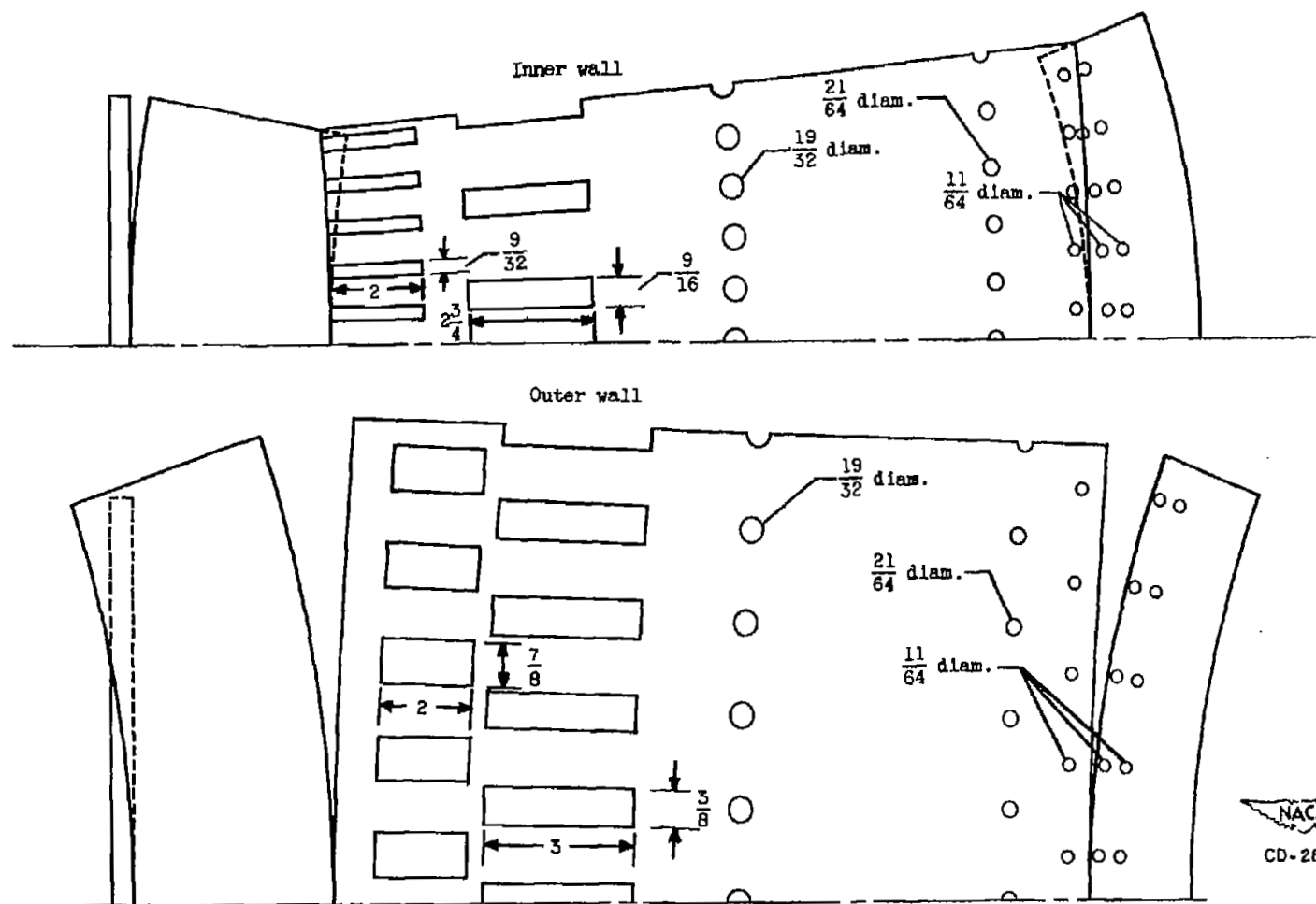
(a) Model 1.

Figure 22. - Developed view of combustor liner design for three models. (Dimensions are in inches.)



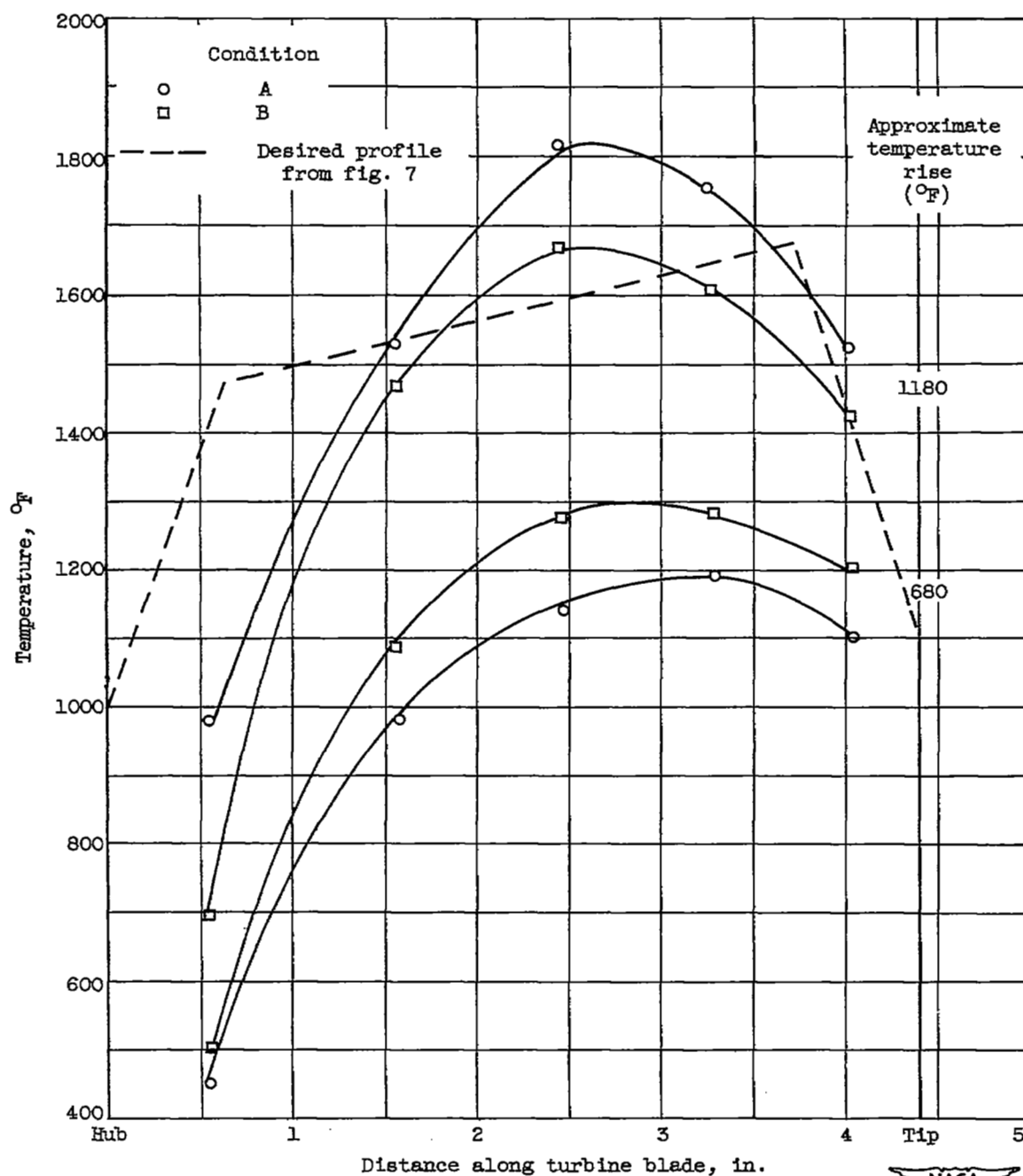
(b) Model 2.

Figure 22. - Continued. Developed view of combustor liner design for three models. (Dimensions are in inches.)



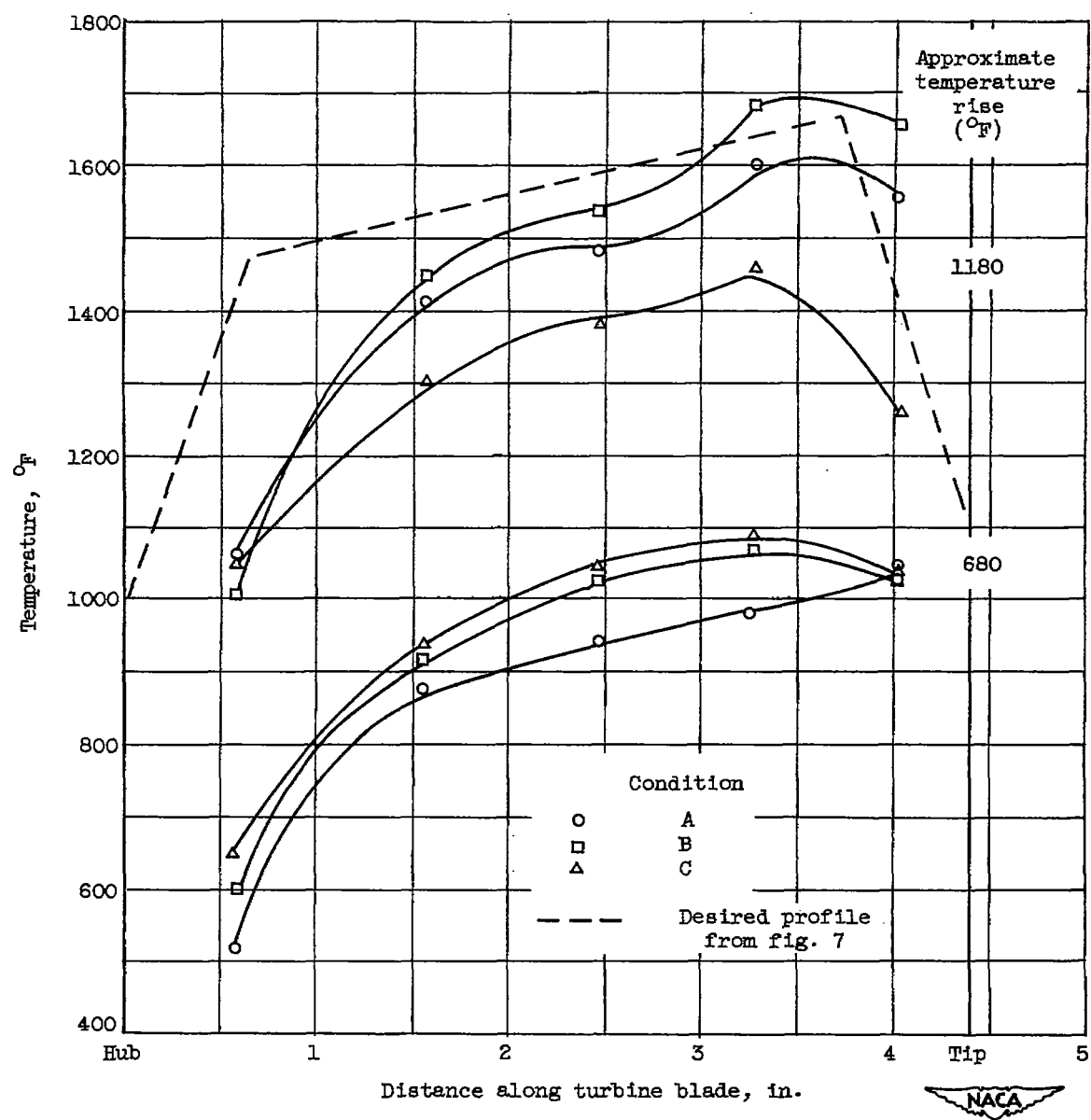
(c) Model 3.

Figure 22. - Concluded. Developed view of combustor liner design for three models. (Dimensions are in inches.)



(a) Model 1.

Figure 23. - Combustor-outlet temperature profiles.



(b) Model 2.

Figure 23. - Continued. Combustor-outlet temperature profiles.

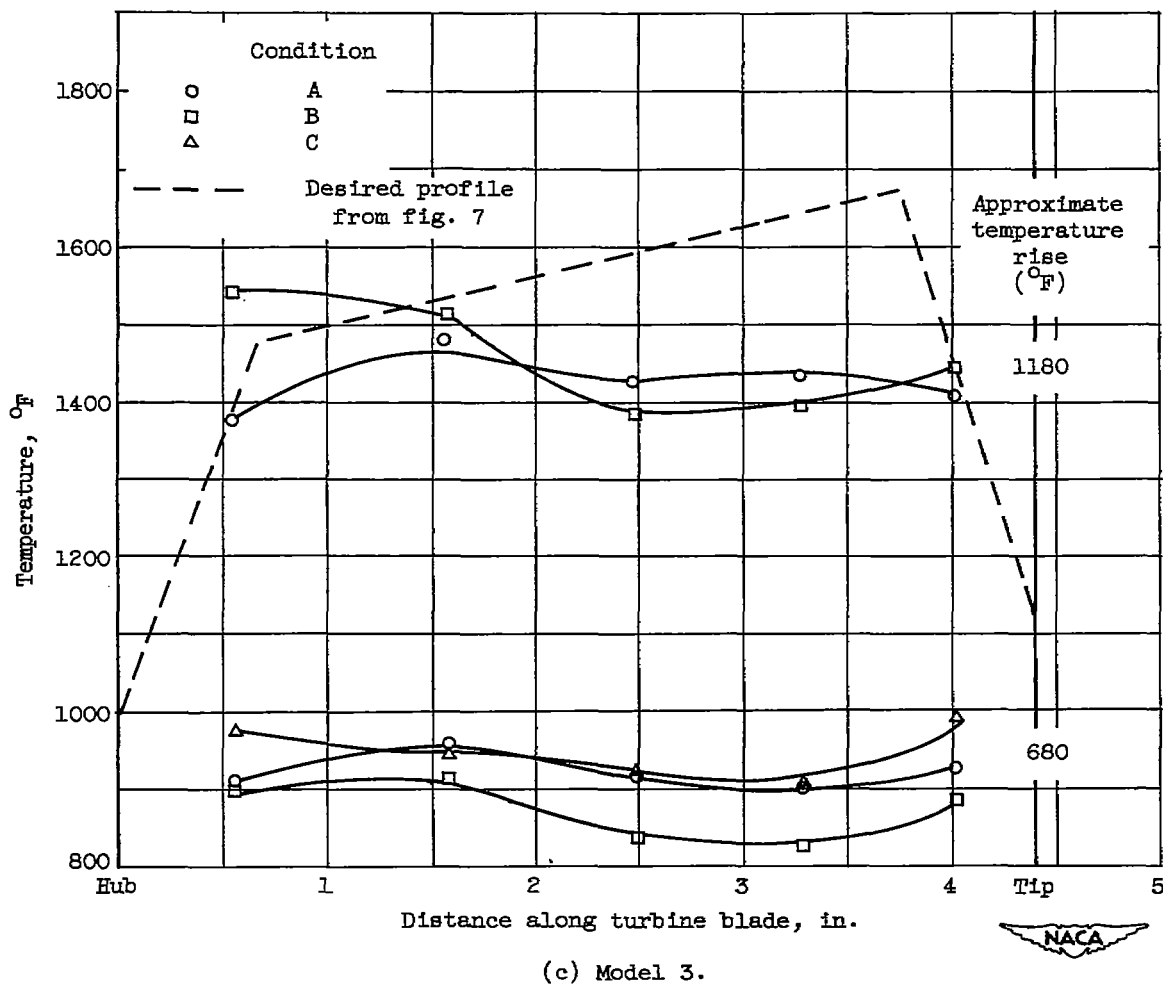


Figure 23. - Concluded. Combustor-outlet temperature profiles.

SECURITY INFORMATION

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